Precision studies of Drell-Yan p_T distributions and polarization angular coefficients in Z boson decays with the ATLAS detector

Lowx 2016, June 2016

Kristof Schmieden, on behalf of the ATLAS collaboration

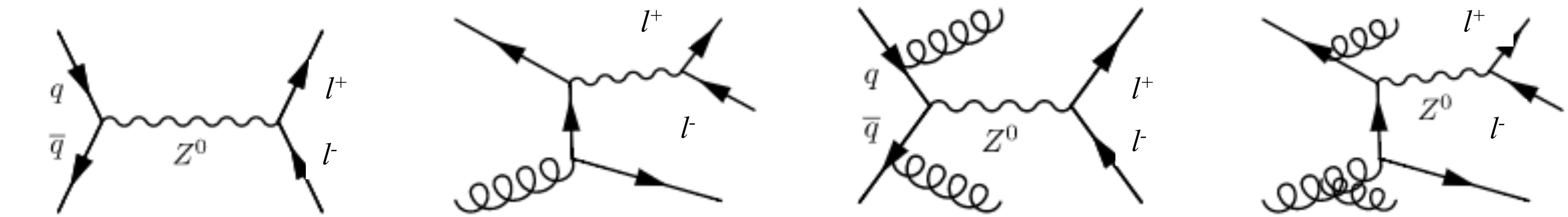
Overview

- Motivation for these measurements

- Details of
  - Z/γ^* transverse momentum and ϕ^* arXiv:1512.02192
  - Angular coefficients A_i arXiv:1606.00689

- Whats next?

Motivation

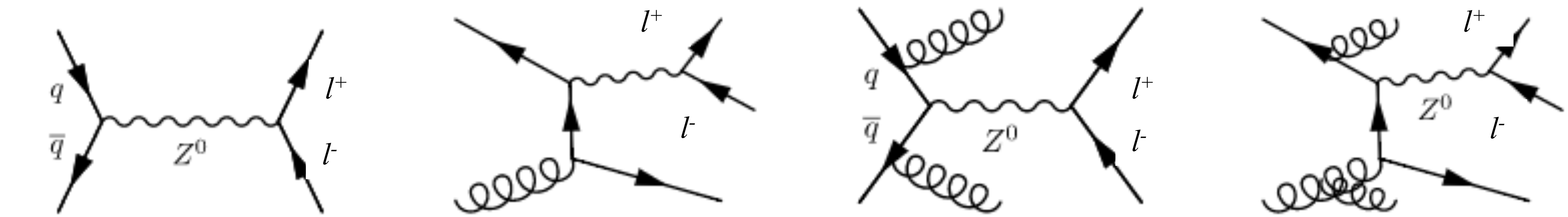


(a) Leading Order (b) Next to leading order (c) Parton shower (d) Next to leading + parton shower

$p_T(ll) \sim 0$ $p_T(ll) > 0$

- Probes perturbative QCD
- Non perturbative effects / soft gluon resummation
- Parton shower effects
- Behavior of different MC modeling approaches

Motivation



(a) Leading Order (b) Next to leading order (c) Parton shower (d) Next to leading + parton shower

$p_T(ll) \sim 0$ $p_T(ll) > 0$

- Full event kinematics parametrized by 8 angular coefficients, dependent on p_T, Y, M_{ll}

Valid to all orders in QCD

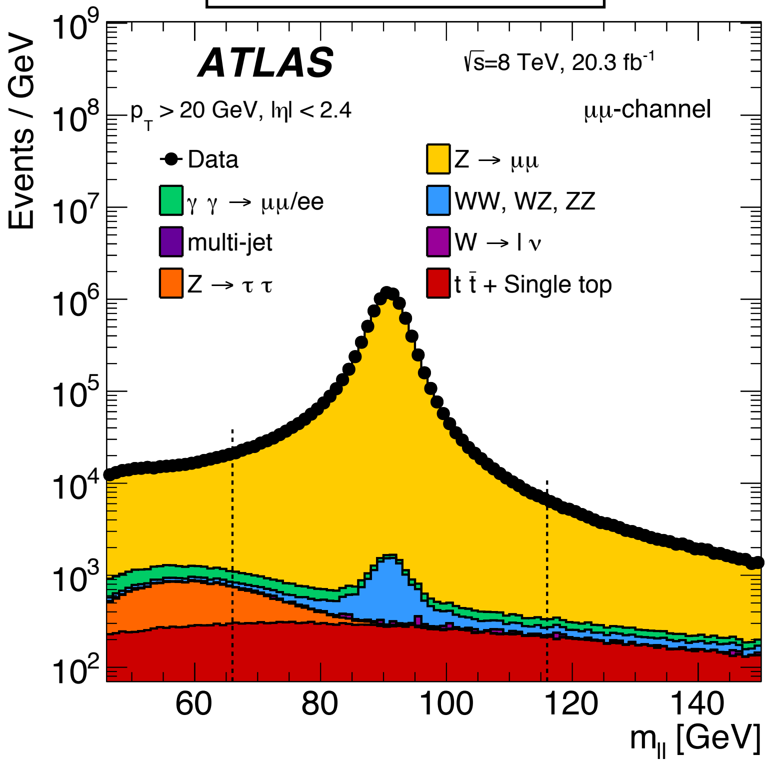
$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z} \left\{ (1+\cos^2\theta) + \frac{1}{2} A_0 (1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \right\}$$

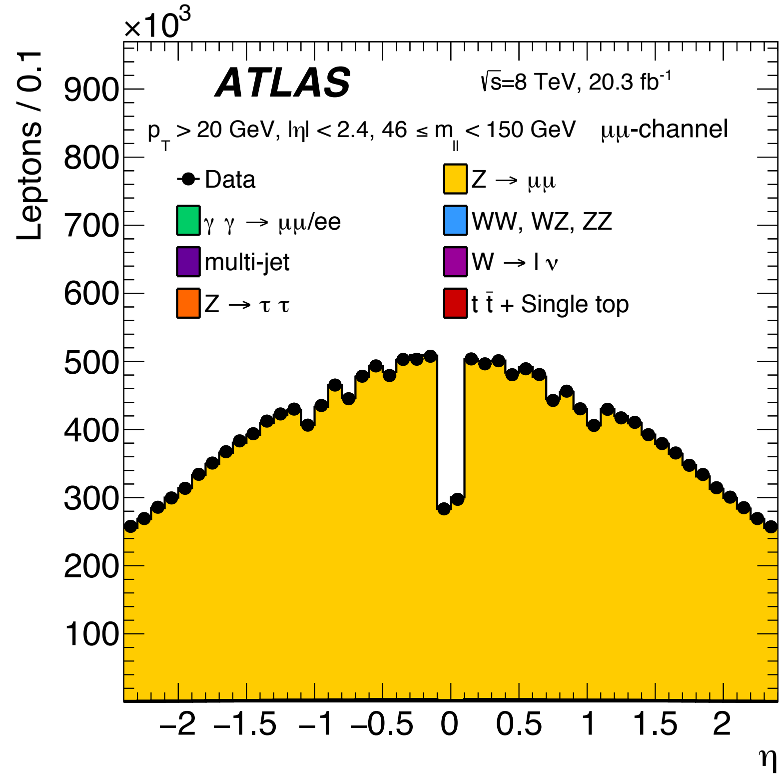
- Test QCD predictions to all orders of α_s
- Includes Spin-correlations of all particles
- Sensitive to various SM parameters

Measurement of the Transverse Momentum p_T

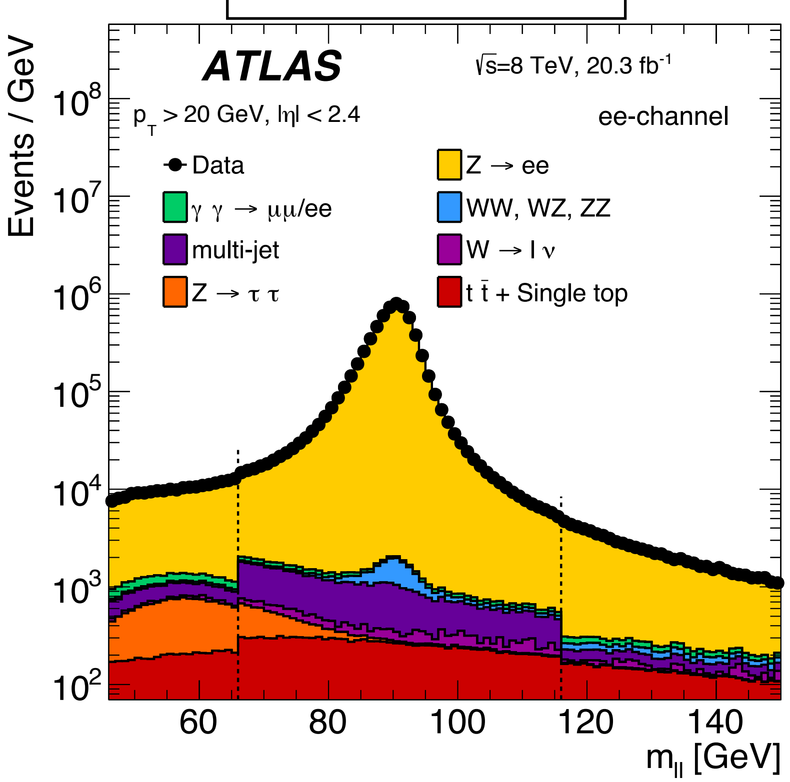
Measurement of p_T^{ll} and ϕ^*_η

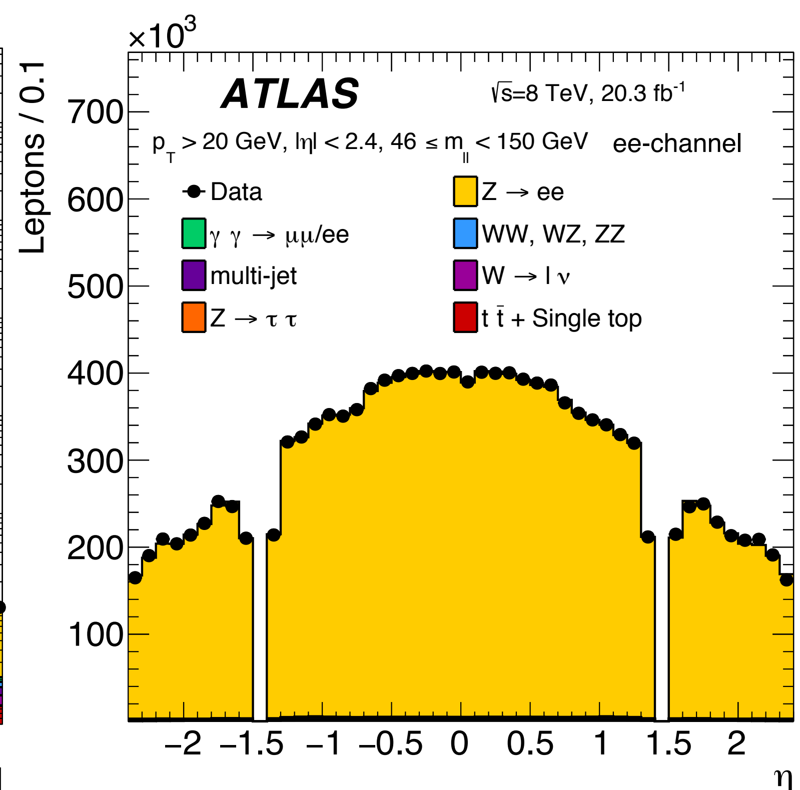
Muon channel





Electron channel



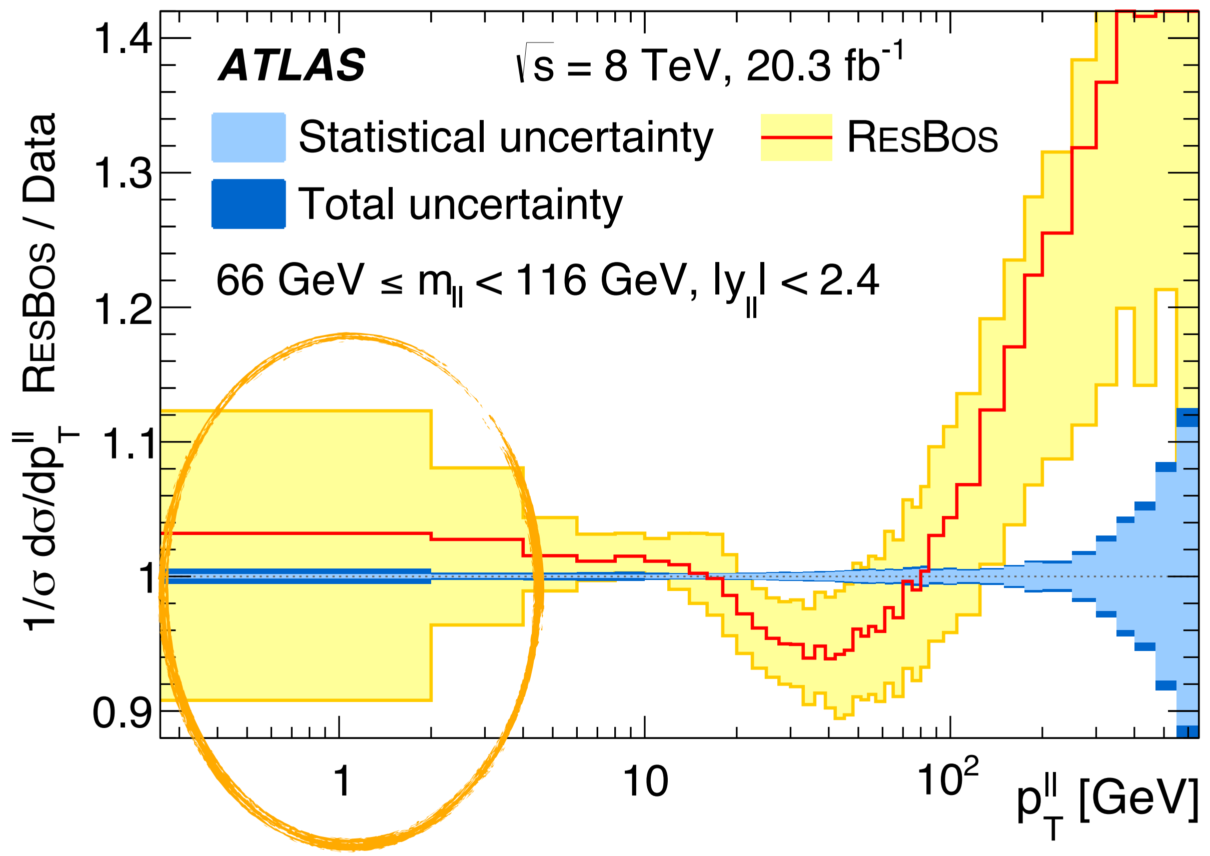


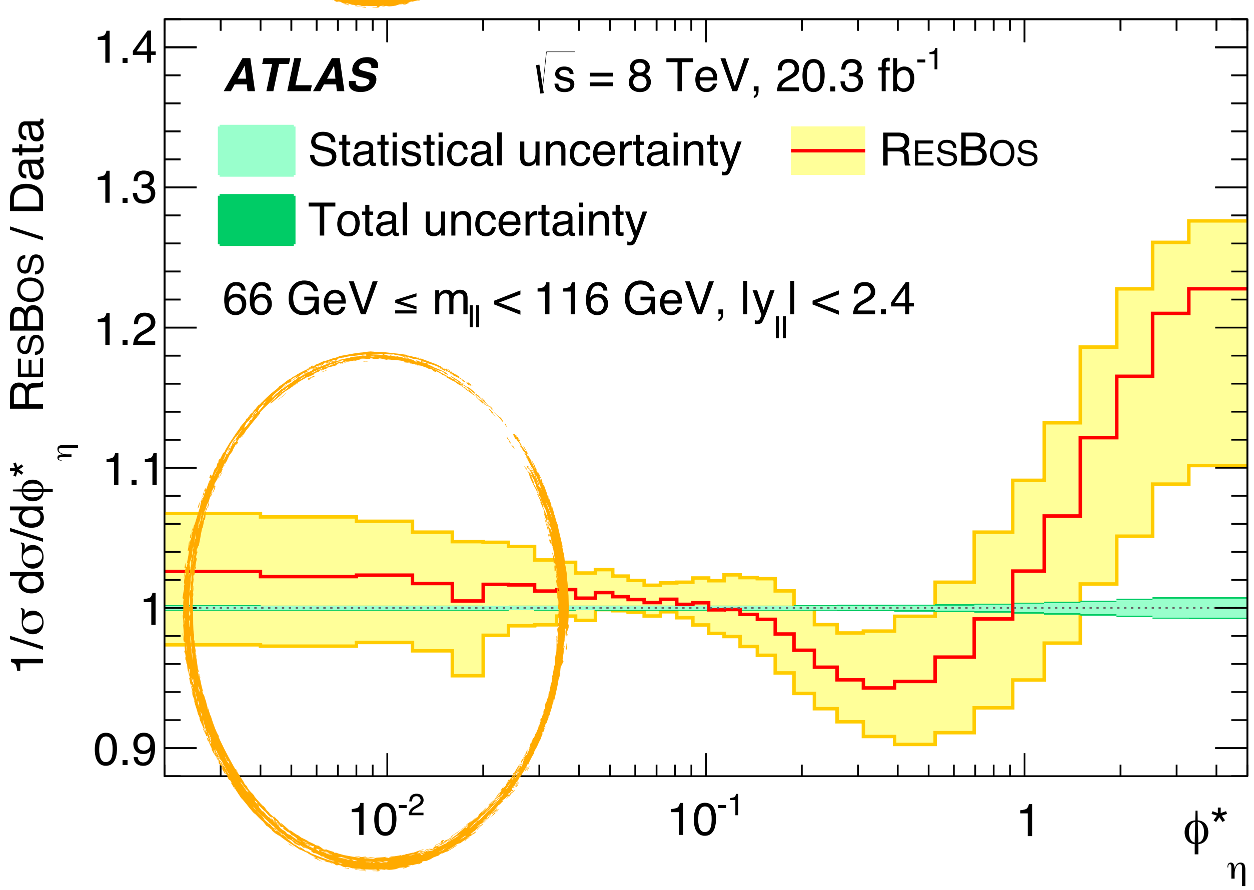
- Data collected during 2012
  - $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
- ee and μμ channel
- Fiducial Volume

  $p_{\mathrm{T}} > 20\,\mathrm{GeV}$

  $|\eta| < 2.4$
- MC signal:
  - POWHEG+PYTHIA
- Backgrounds:
  - EW & ttbar from MC
  - QCD multijet: data-driven

Measurement of p_{T}^{ll} and ϕ_η^*





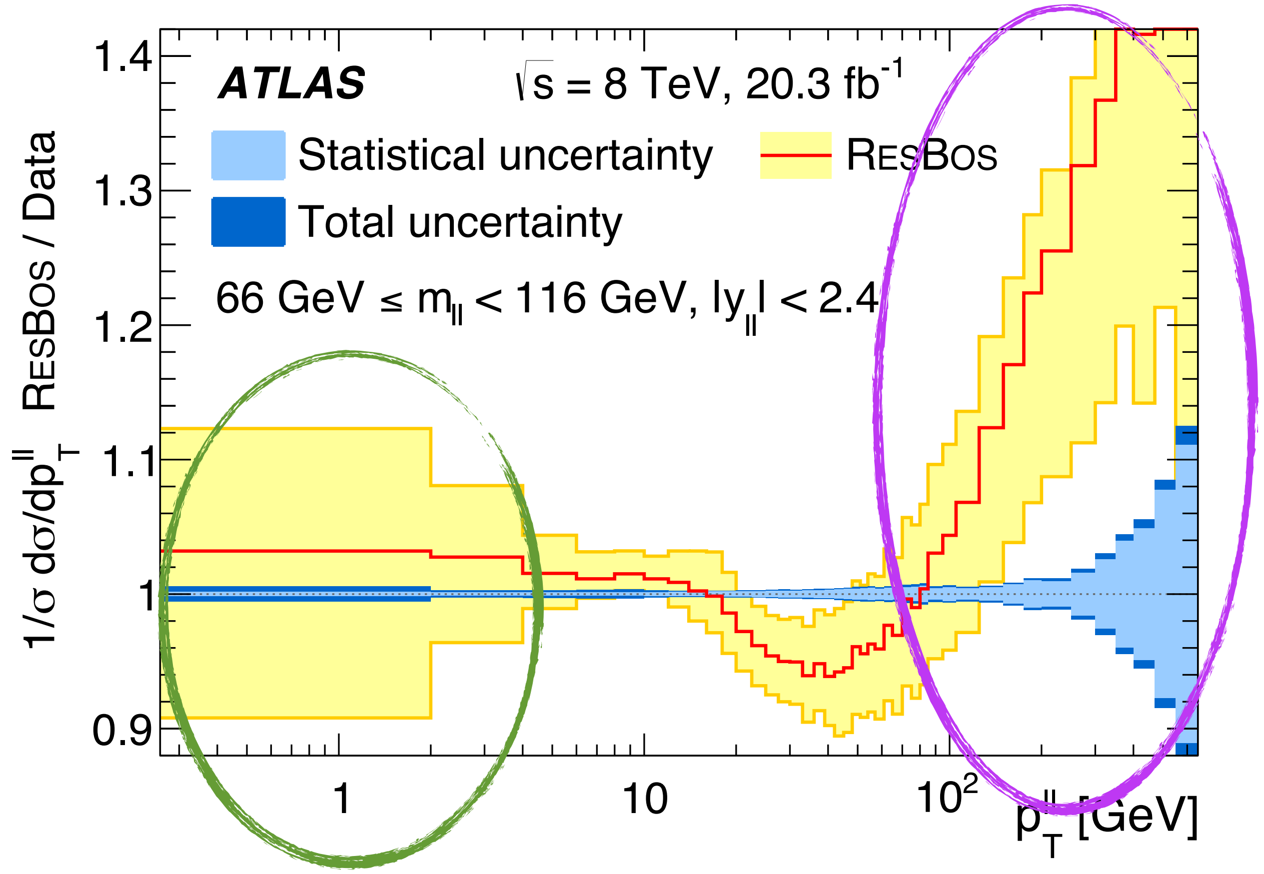
azimuthal angle between the two leptons

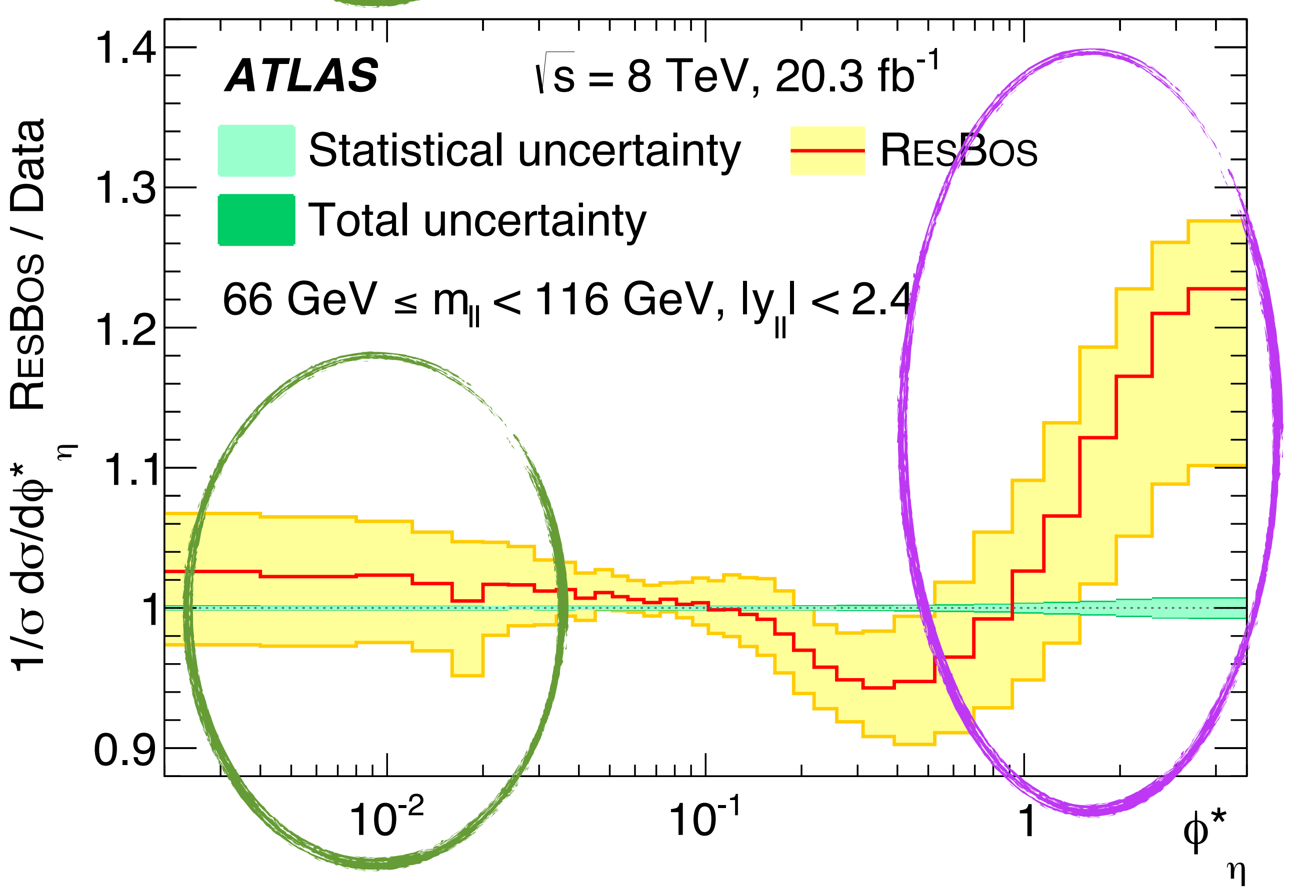
$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_\eta^*)$$

$$\theta_\eta^* = \arccos\left(\tanh\left(\frac{\eta^- - \eta^+}{2}\right)\right)$$

- Depends only on measured angles
  - Better resolution compared to momentum measurements
    - In particular for low pT values
  - $\sqrt{2} m_Z \phi_\eta^* \approx p_{\mathrm{T}}^{ll}$
- x-axes in Plots are aligned

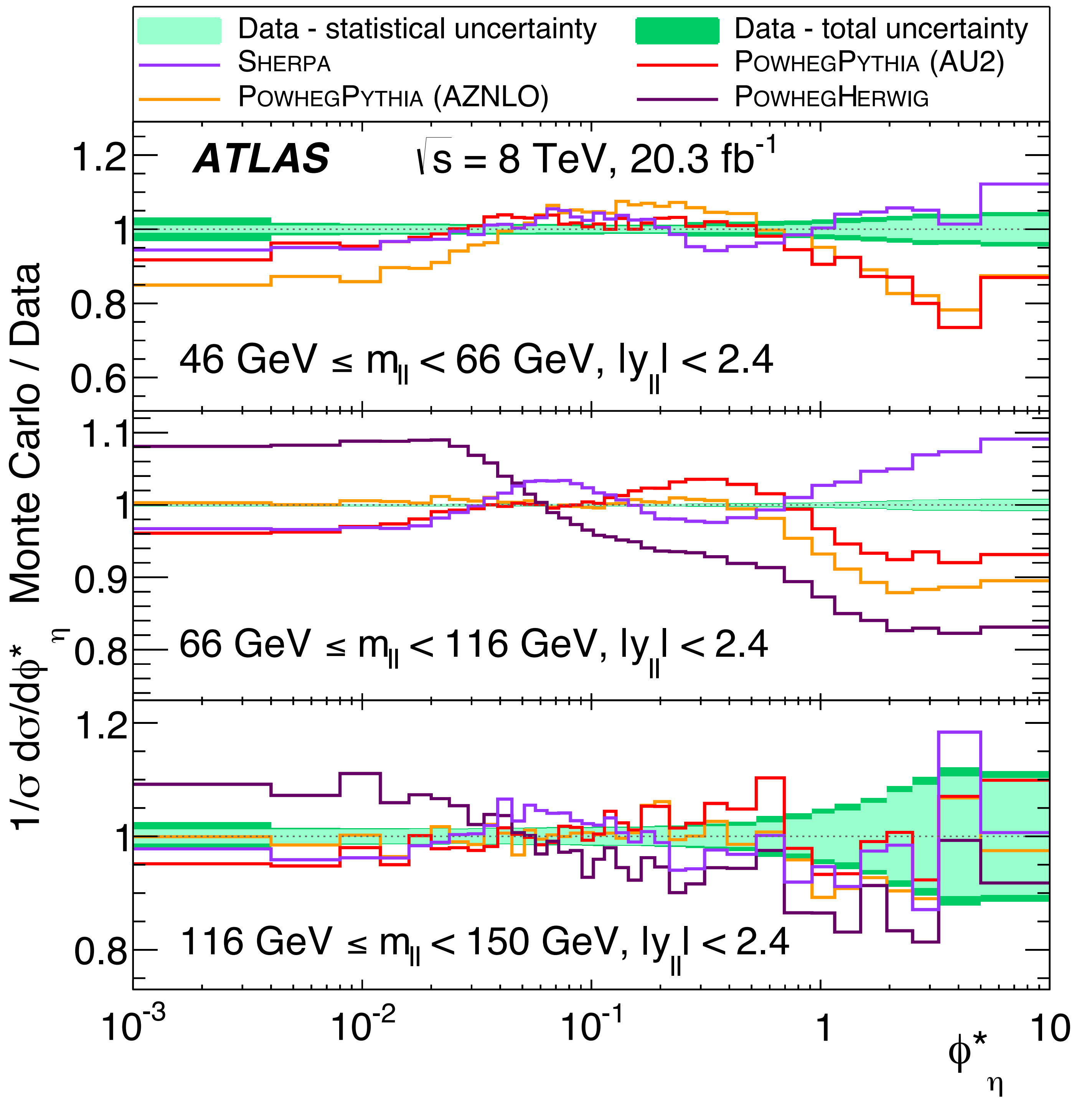
Measurement of p_{T}^{ll} and ϕ_{η}^{*}





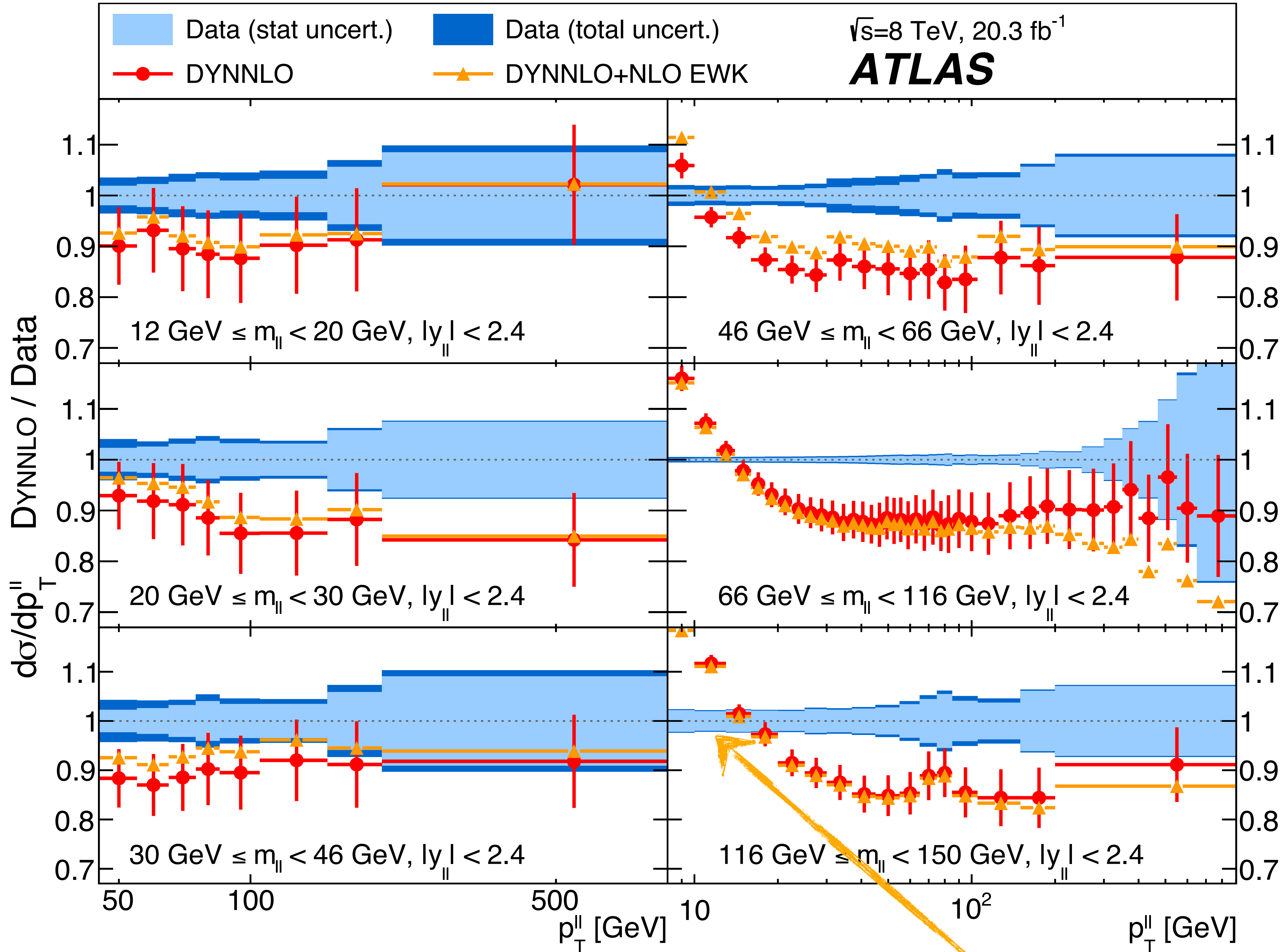
- Low range dominated by:
  - Non perturbative effects
  - Soft gluon resummation
    - ResBos predictions agree with data
- High range dominated by:
  - Emission of hard partons
    - ResBos predictions not consistent with data

Comparison to parton-shower Simulations



- Comparison in 3 regions of m_{ll}
- 2 individual Pythia tunes:
  - AZNLO done on 7 TeV data at Z-peak
  - AU2
- Significant disagreement between simulation & data in peak region
- Also significant disagreement between PowHeg and Sherpa
  - Particularly for large ϕ^* values

Electroweak corrections



- Predictions low by ~15% in all m_{ll} bins
- No significant impact of NLO EWK corrections

Expected due to soft-gluon emissions

Angular Coefficients A_i

A bit of Theory

Differential cross section for

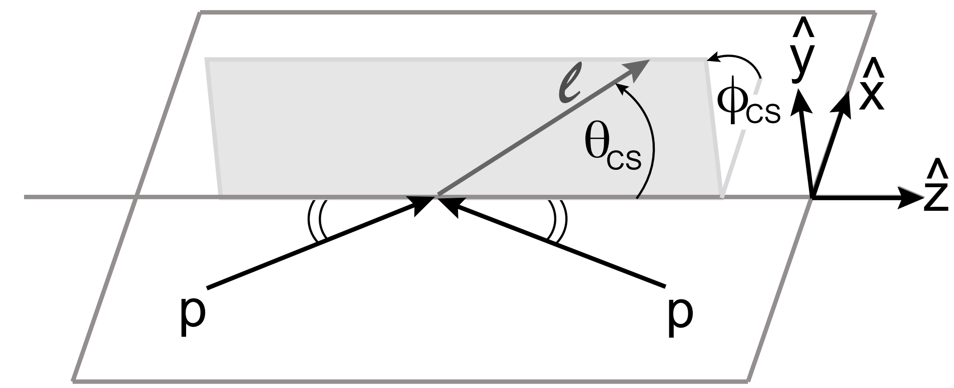
$$pp \to Z/\gamma^* + X \to l^+l^- + X$$

$$\frac{d\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2} A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\Big\}$$

Angular distributions parametrized by coefficients $\mathbf{A_i}$

Angles in **Collins-Soper** Frame:



- Rest frame of di-lepton system
- z-axis bisecting directions of incoming proton momenta
- Direction of z-axis defined by longitudinal boost of di-lepton system

A bit of Theory

Orthogonal polynomials used to parametrize angular distribution:

$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi)\,d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}{\int d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}$$

A_i are neither input to theory calculations, nor simulations!

$< 1+\cos^2\theta >$ normalization of unpolarized cross section, also applied to all other P

$<\frac{1}{2}(1-3\cos^2\theta)> = \frac{3}{20}(A_0 - \frac{2}{3})$ longitudinal polarization

$<\sin 2\theta\ \cos\phi> = \frac{1}{5}A_1$ interference term: longitudinal / transverse

$<\sin^2\theta\ \cos 2\phi> = \frac{1}{10}A_2$ transverse polarization

$<\sin\theta\ \cos\phi> = \frac{1}{4}A_3$ product of v-a couplings, sensitive to Weinberg angle

$<\cos\theta> = \frac{1}{4}A_4$ 8/3 * forward backward asymmetry A_{FB}, sensitive to Weinberg angle non-zero already at LO $q\bar{q} \to Z/\gamma^* \to l^+l^-$

$<\sin^2\theta\ \sin 2\phi> = \frac{1}{5}A_5$

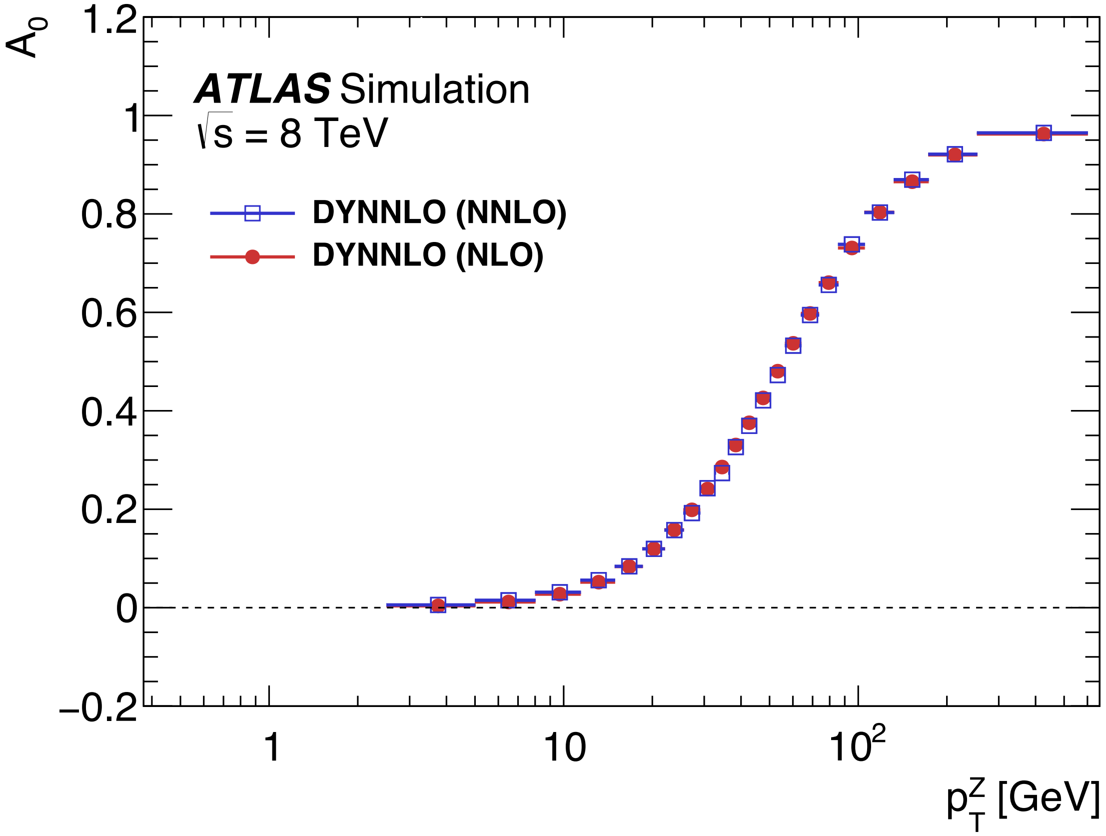
$<\sin 2\theta\ \sin\phi> = \frac{1}{5}A_6$

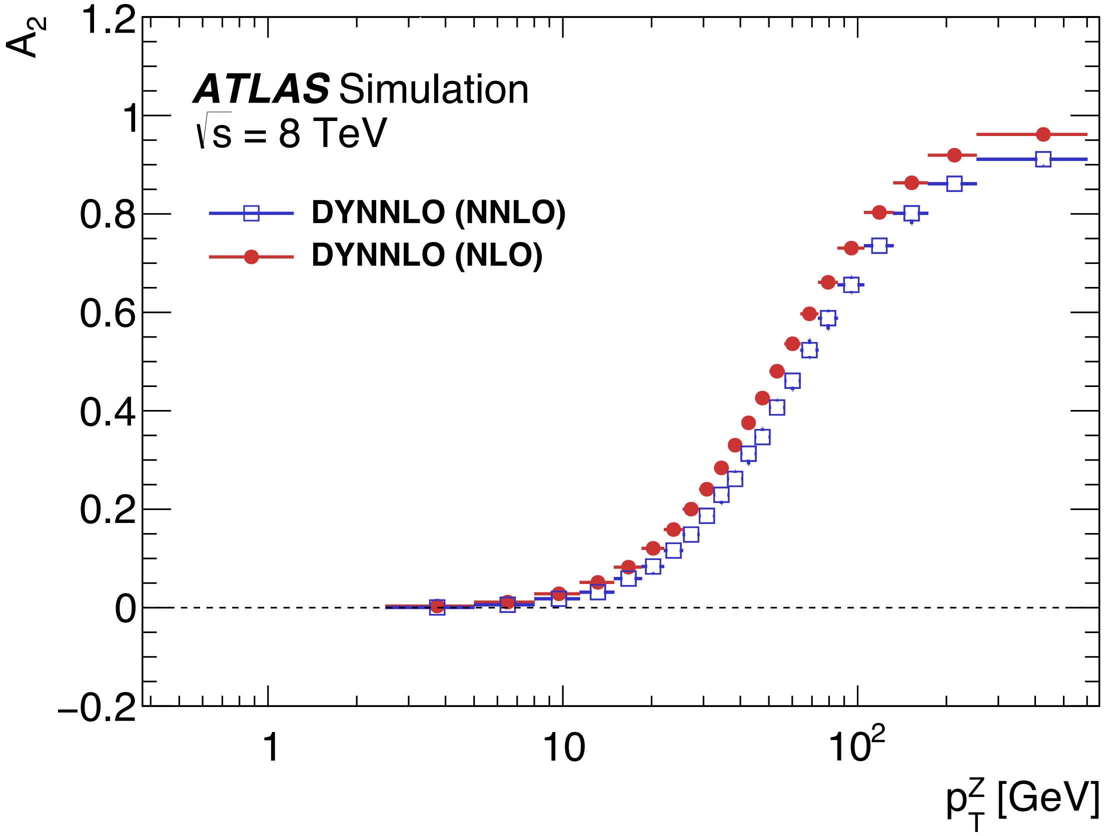
$<\sin\theta\ \sin\phi> = \frac{1}{4}A_7$

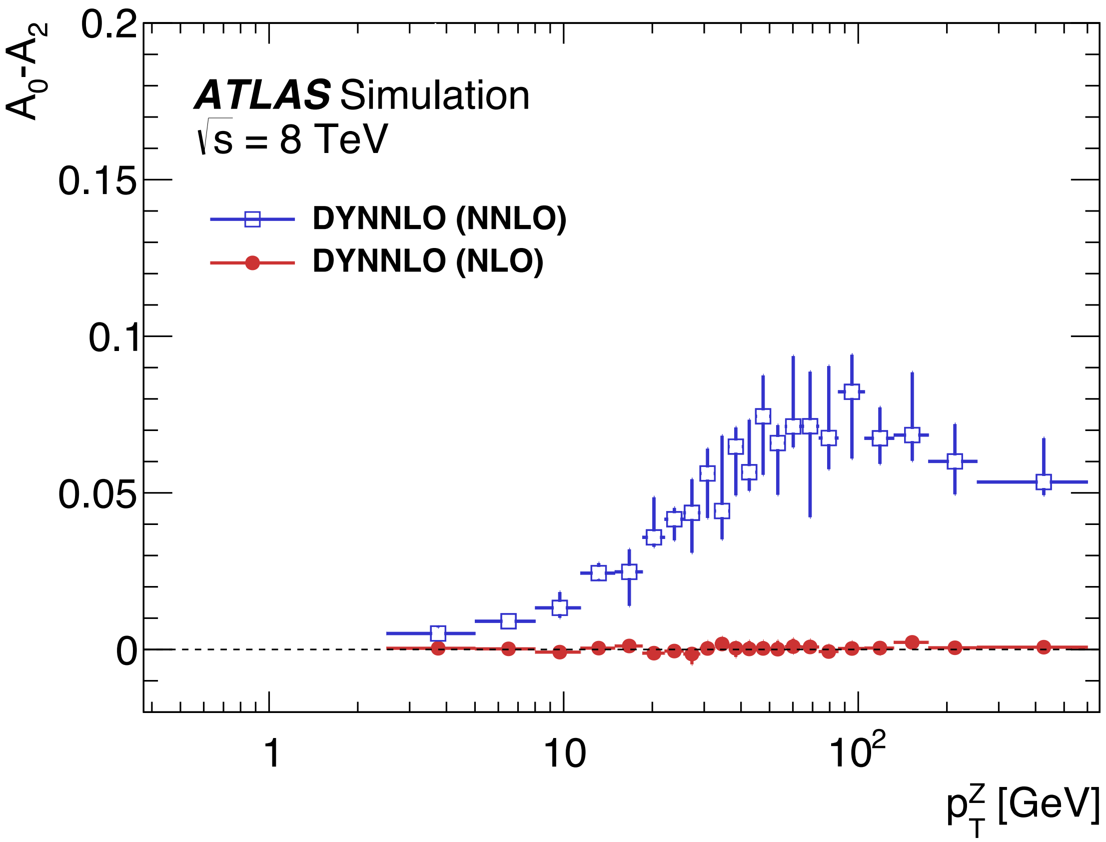
Predicted to be 0 @ NLO

Non zero contributions @ NNLO for large $p_T(Z)$

Impact of higher order QCD corrections

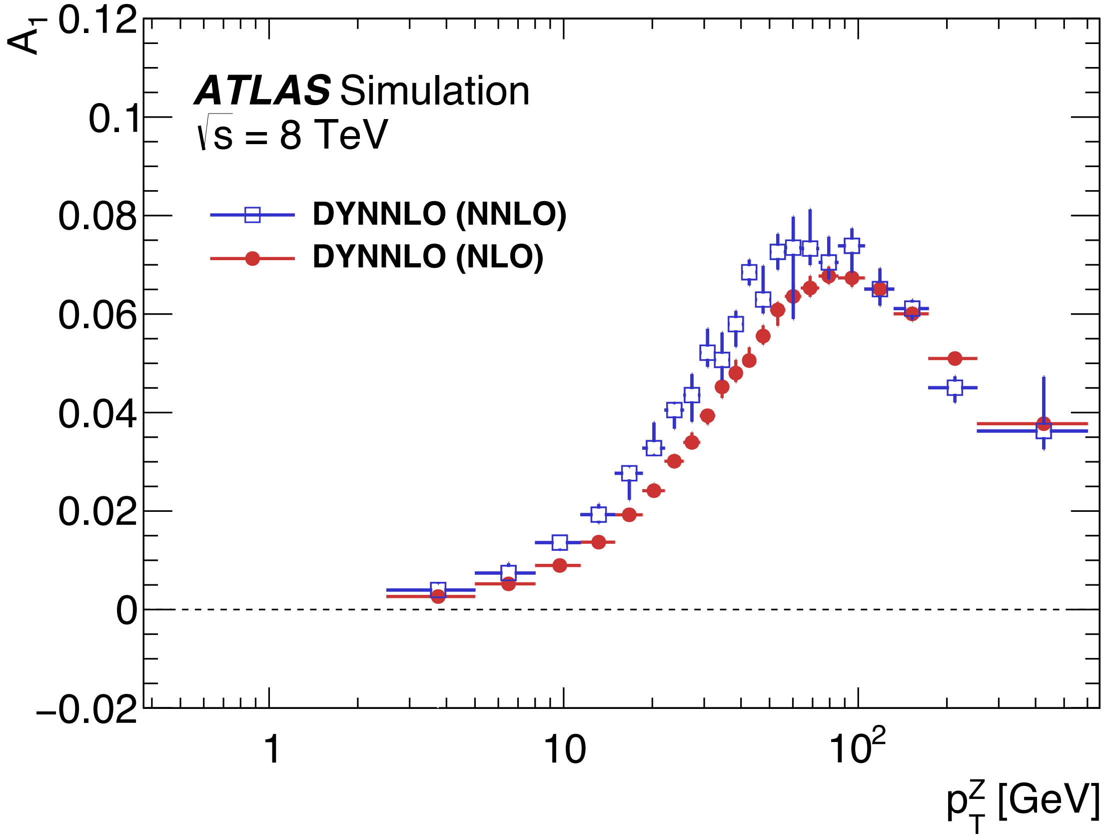


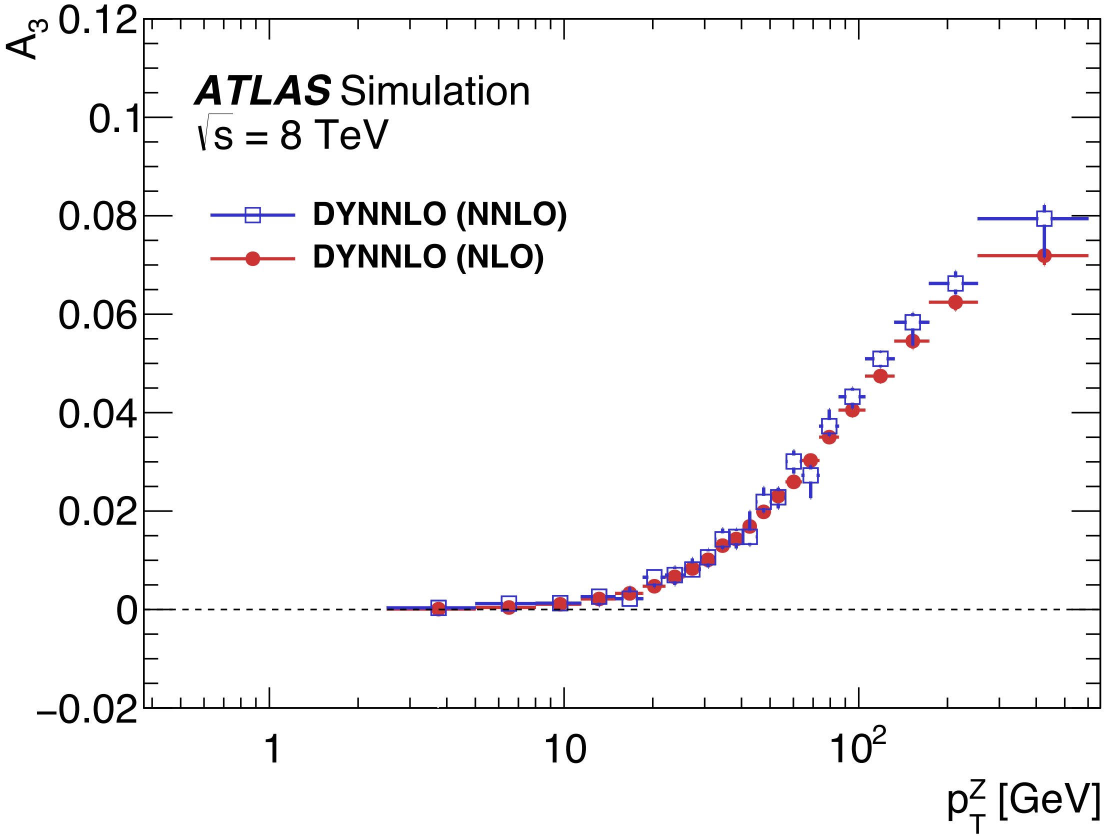


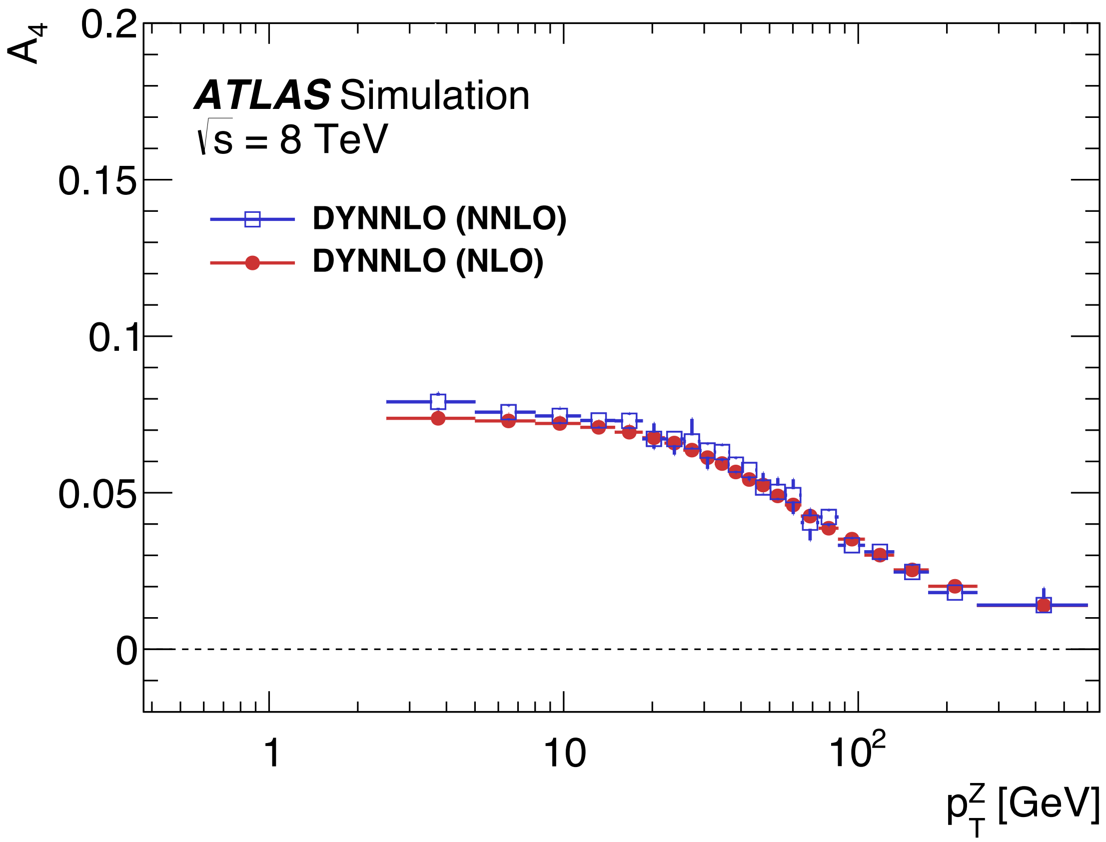


- A_0-A_2: Sensitive to the Spin of the Gluon (Lam-Tung relation)
  - exactly 0 @ NLO
  - A2 changed 10% @ NNLO

Impact of higher order QCD corrections



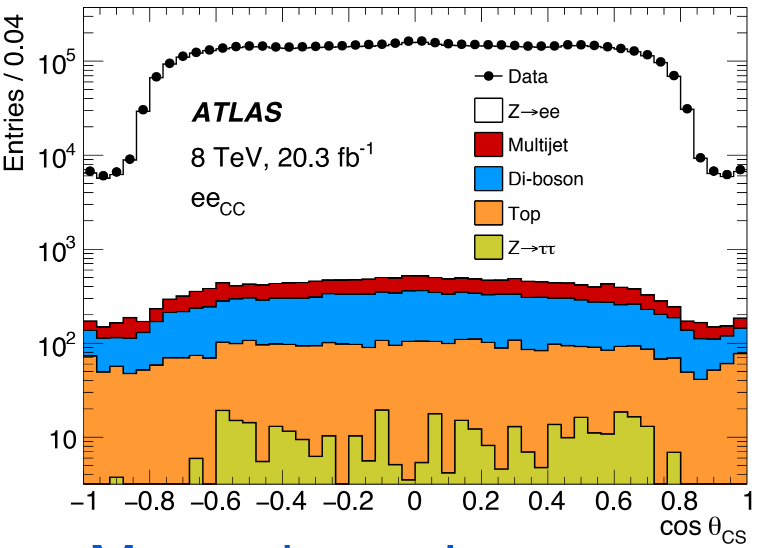


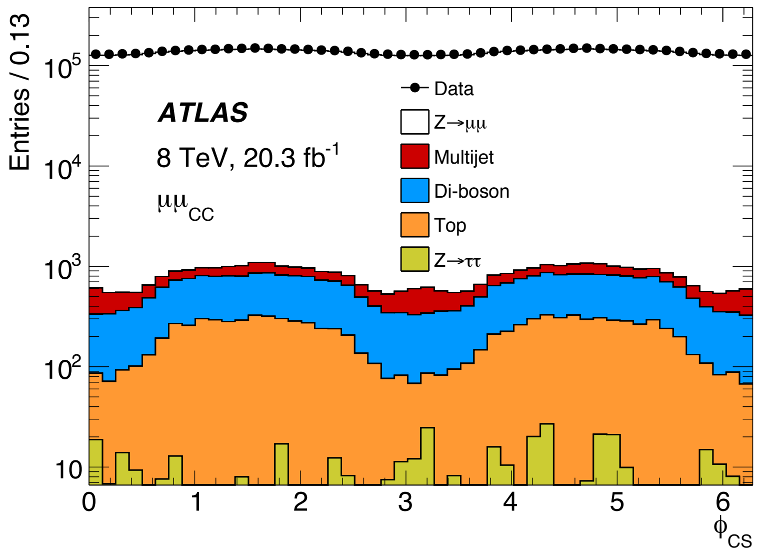


- Only small impact in $A_{1,3,4}$
- No sensitivity with current measurement

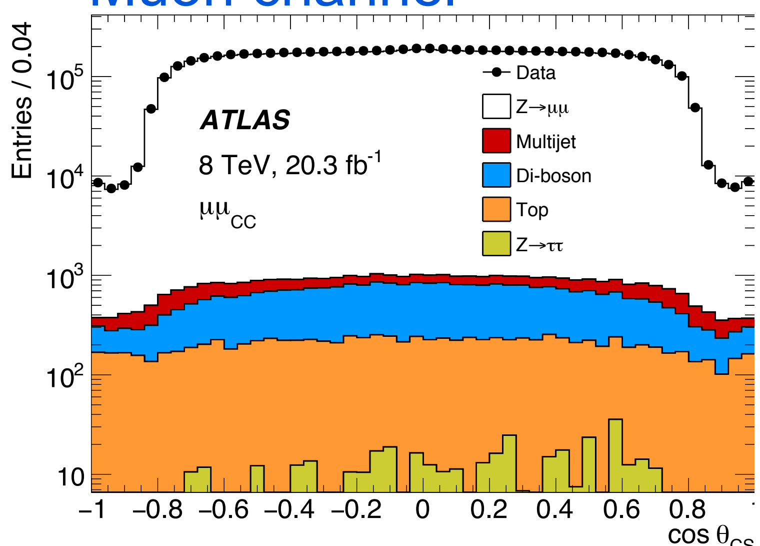
The Measurement - Lepton Selection

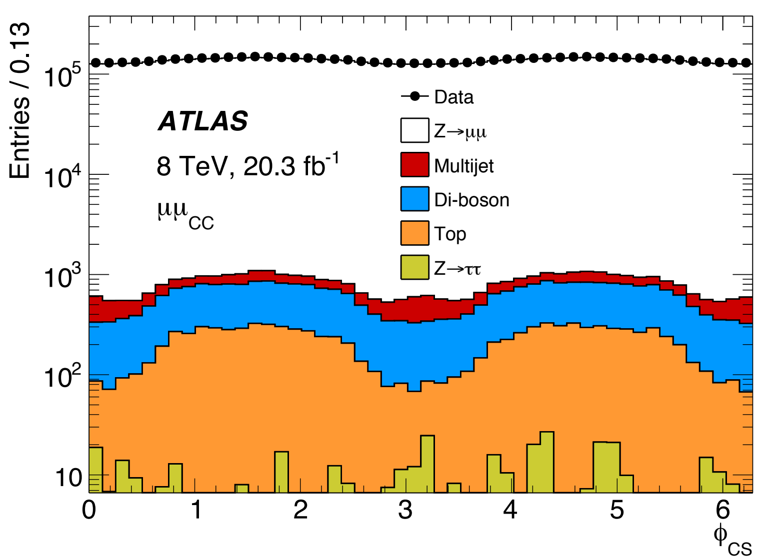
Electron CC channel



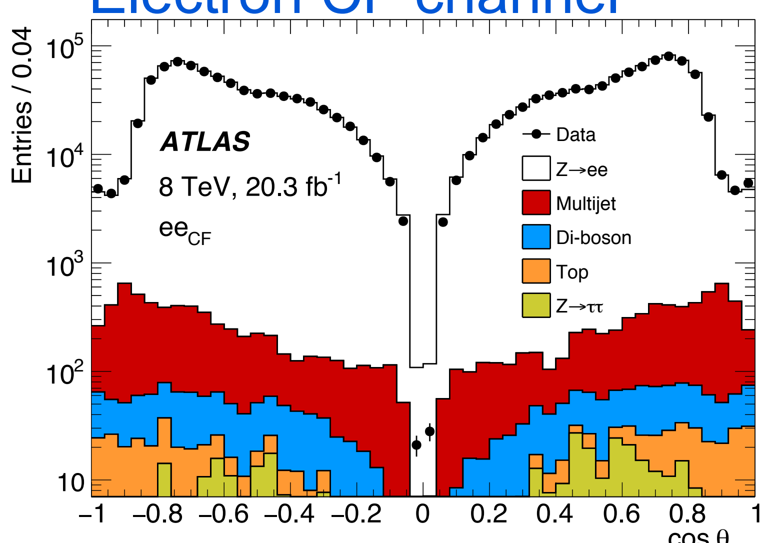


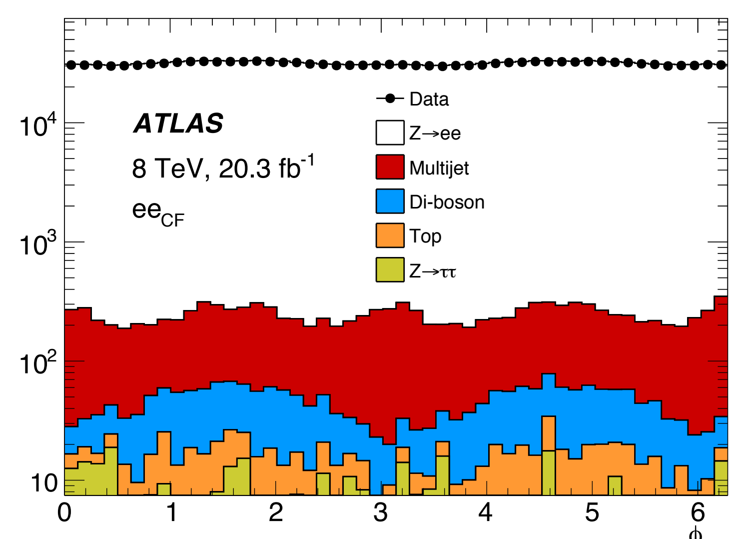
Muon channel





Electron CF channel





- Data collected during 2012
  - $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
- Measurement performed in 3 independent channels:
  - Muons
  - Electrons: central central
  - Electrons: central-forward
- Fiducial Volume:
  - CC & μμ: $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ $|\eta| < 2.4$
  - CF: $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $2.5 < |\eta| < 4.9$
  - OS di-leptons $80 < m_{ll} < 100\,\mathrm{GeV}$
- Backgrounds:
  - EW & ttbar from simulation
  - QCD multi-jet: data driven
- Signal simulation:
  - POWHEG + Pythia

Analysis strategy

- Angular distributions **sculpted by fiducial acceptance**

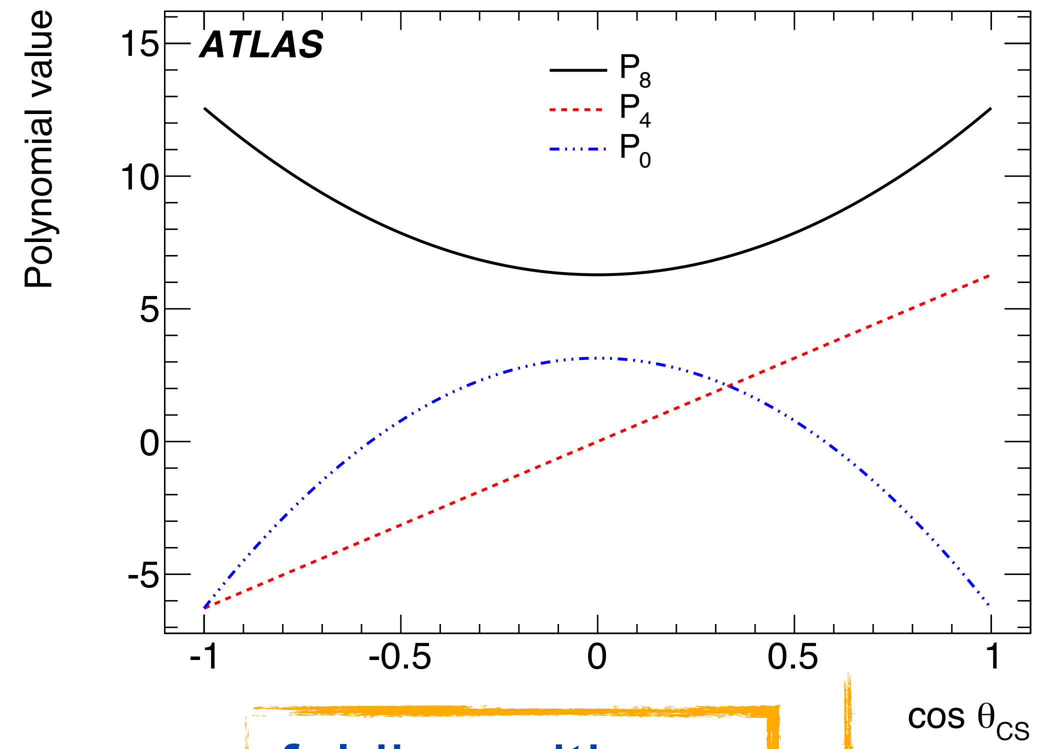
- Polynomials are „folded“ into reconstruction space
  - Simulation used to model acceptance, efficiencies & resolution
  - 3D folding in cosθ, ϕ , p^{ll}_T

- Folded polynomials (templates) fitted to measured angular distributions

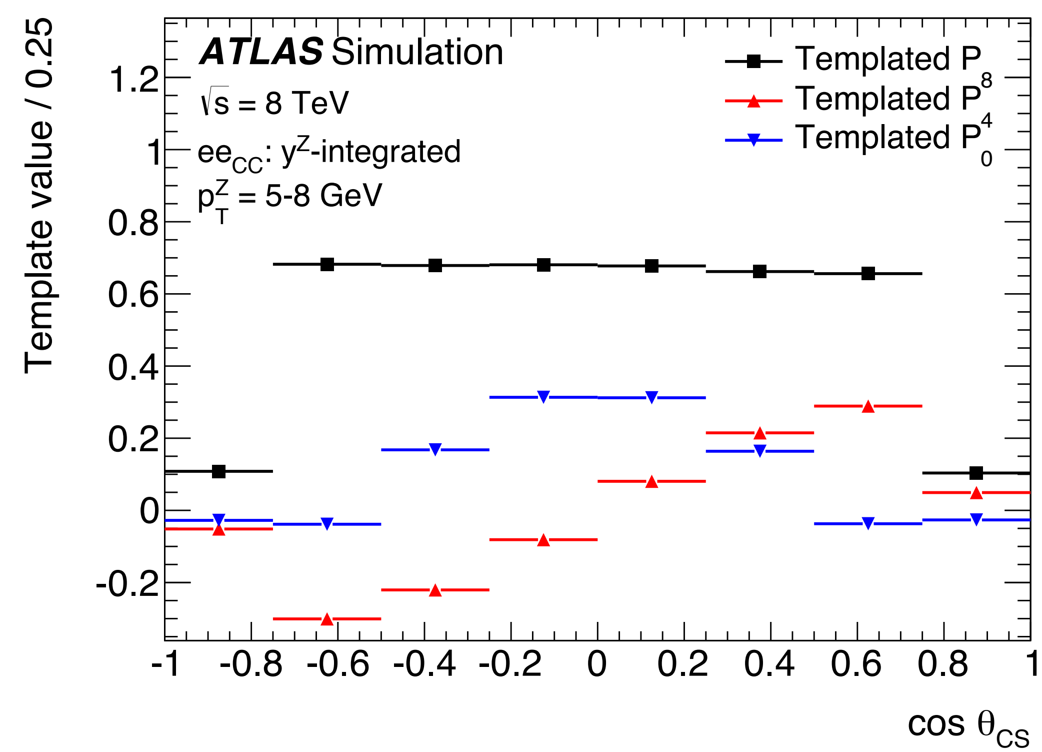
- Angular coefficients A_i normalize the templates relative to each other
  - A_i extracted from fit

- Overall normalization done in $p_T(Z)$

- Fit implemented as maximum likelihood fit
  - Nuisance parameter for each systematic uncertainty incorporated
  - Background templates included

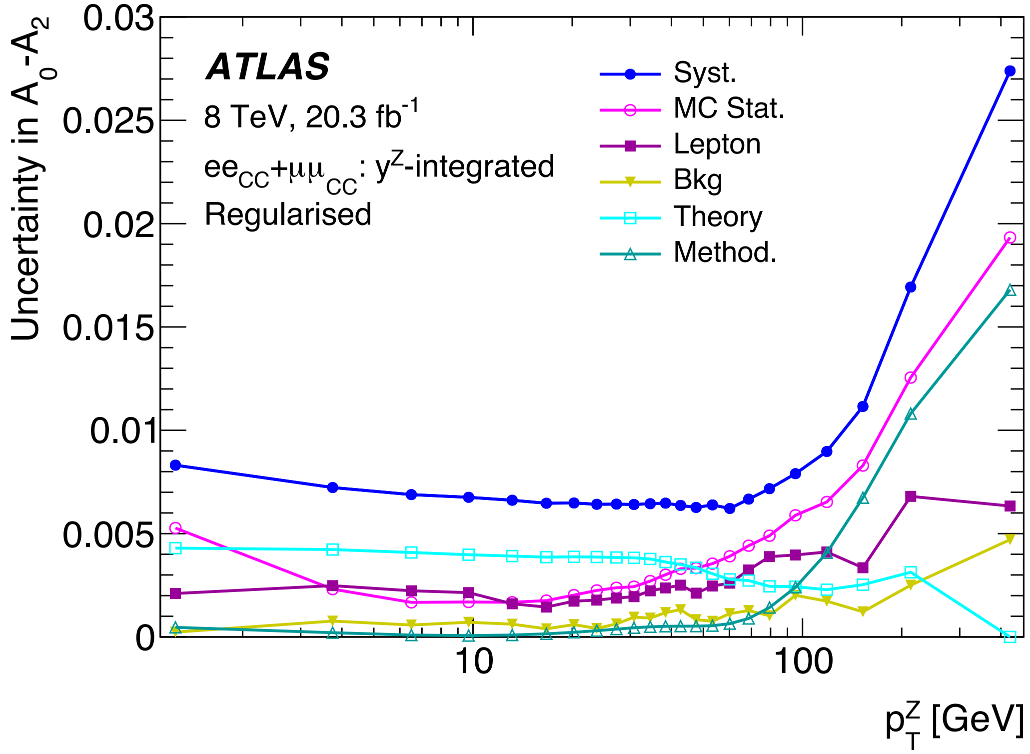


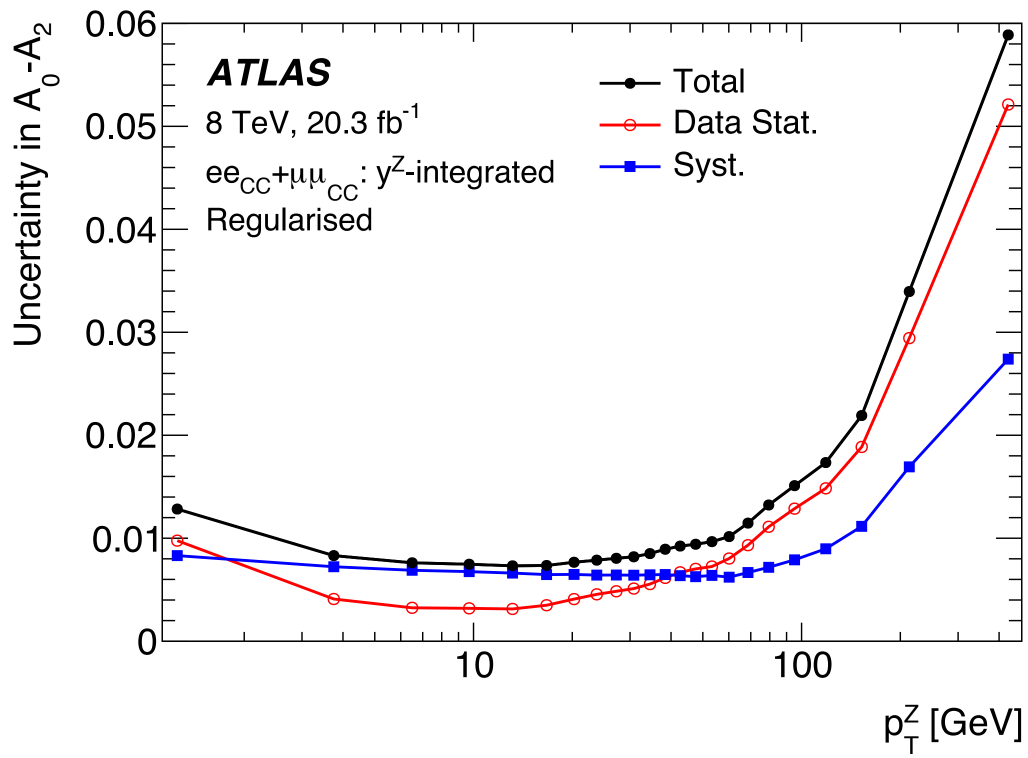
folding with detector effect



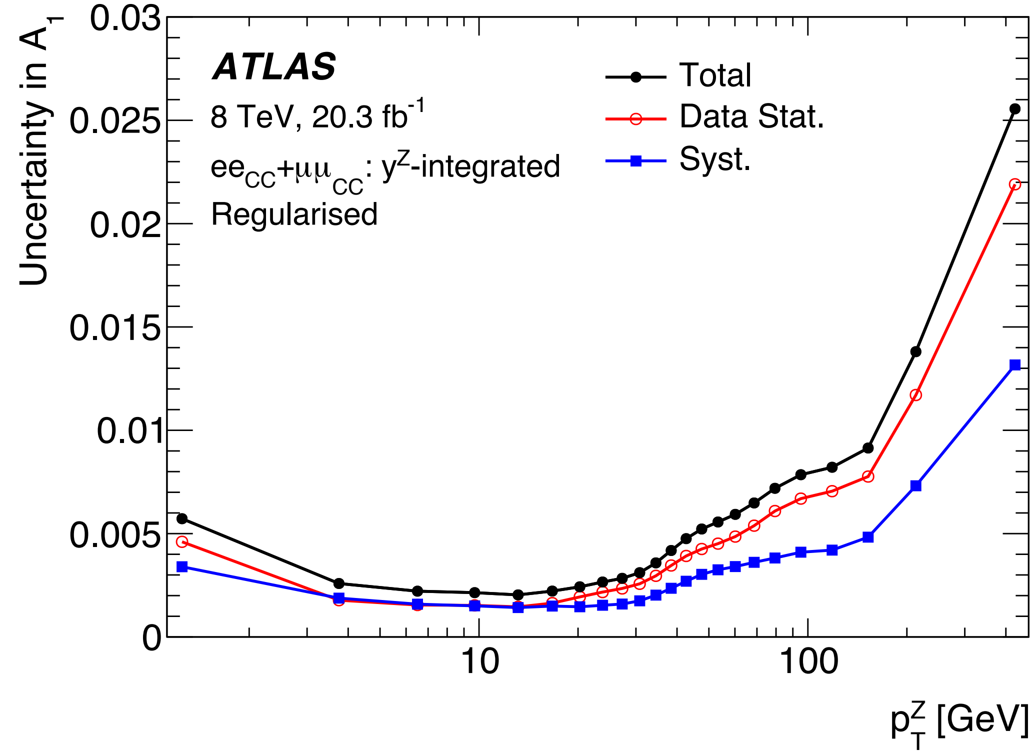
A glance at Uncertainties

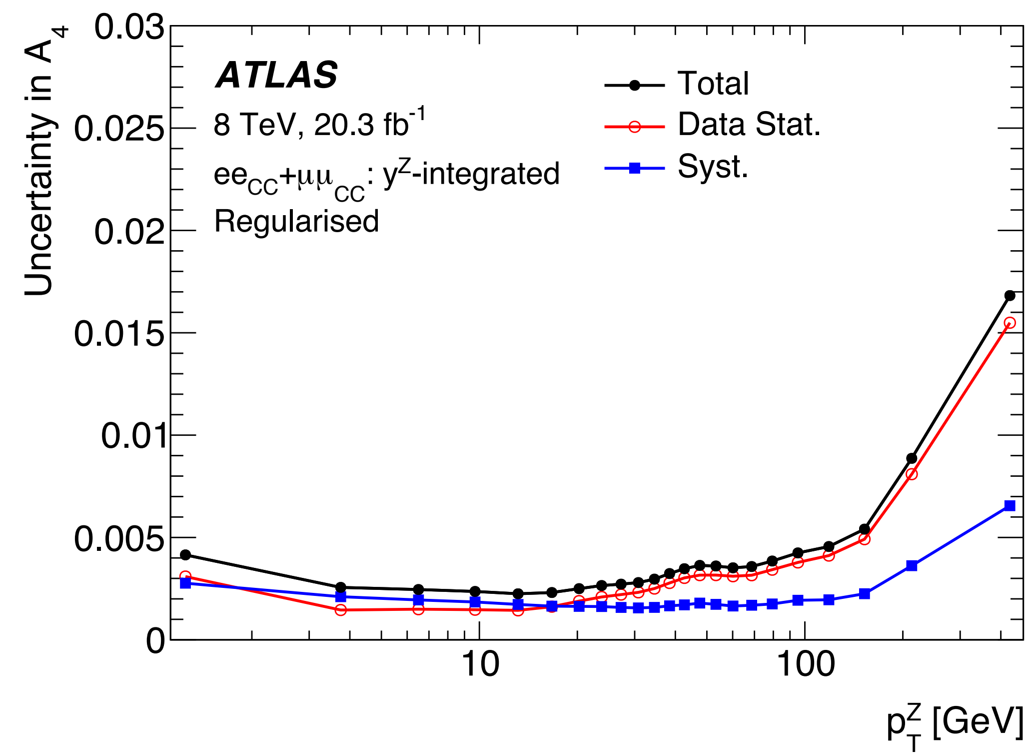
- Breakdown of systematic uncertainties





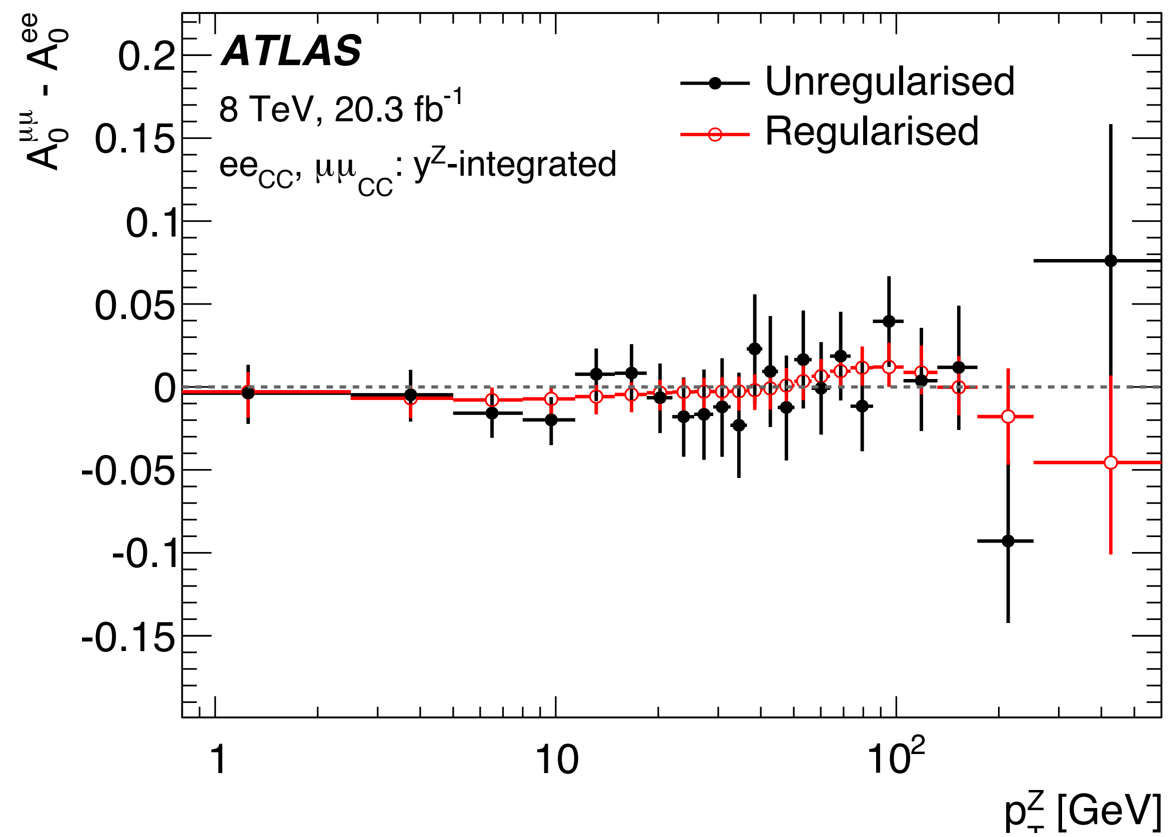
- Total uncertainties
  - Very similar shape for all A_i

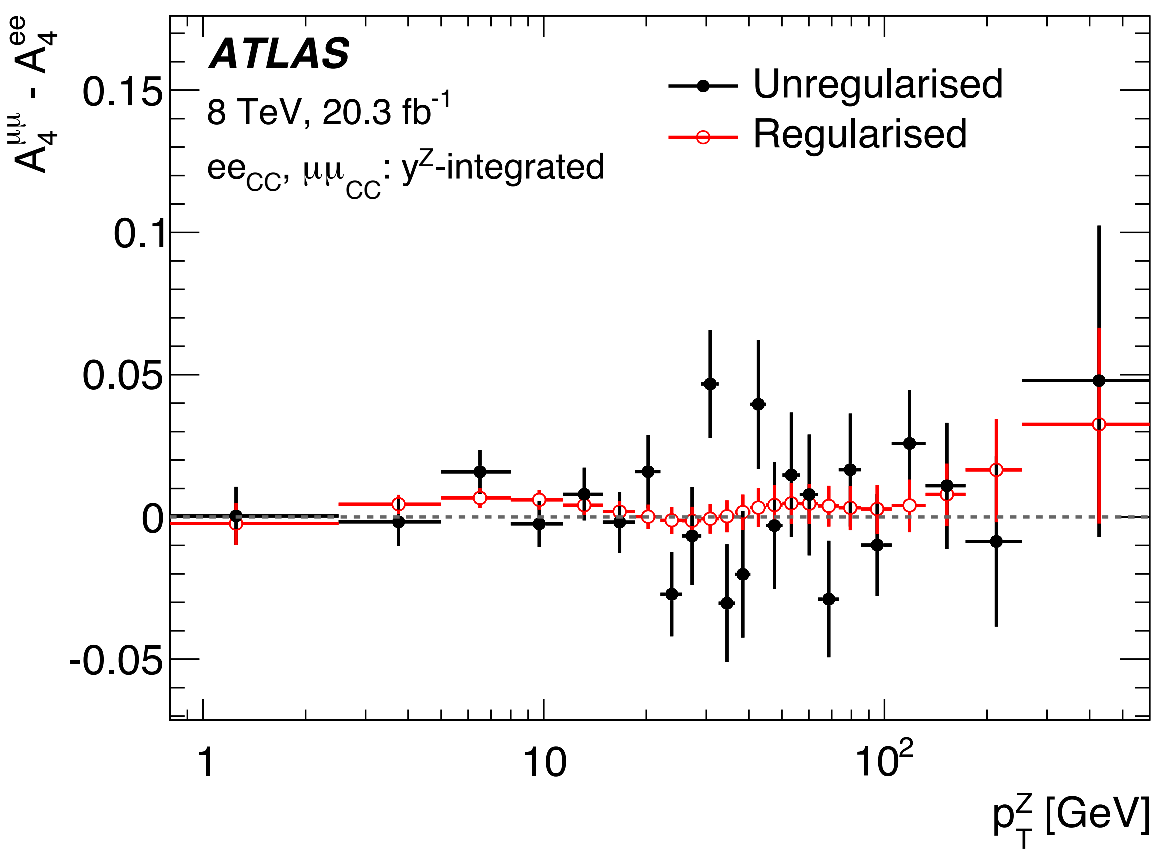


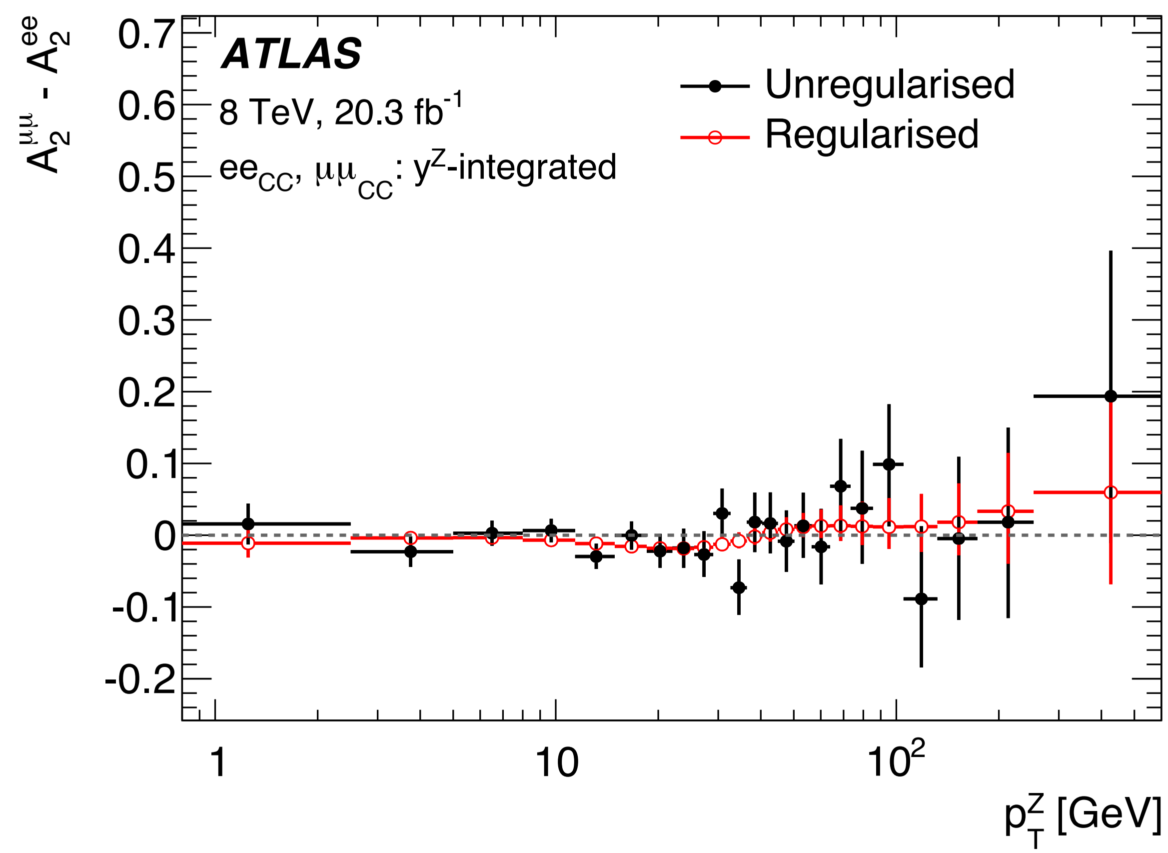


Measurement Results - Compatibility ee / μμ

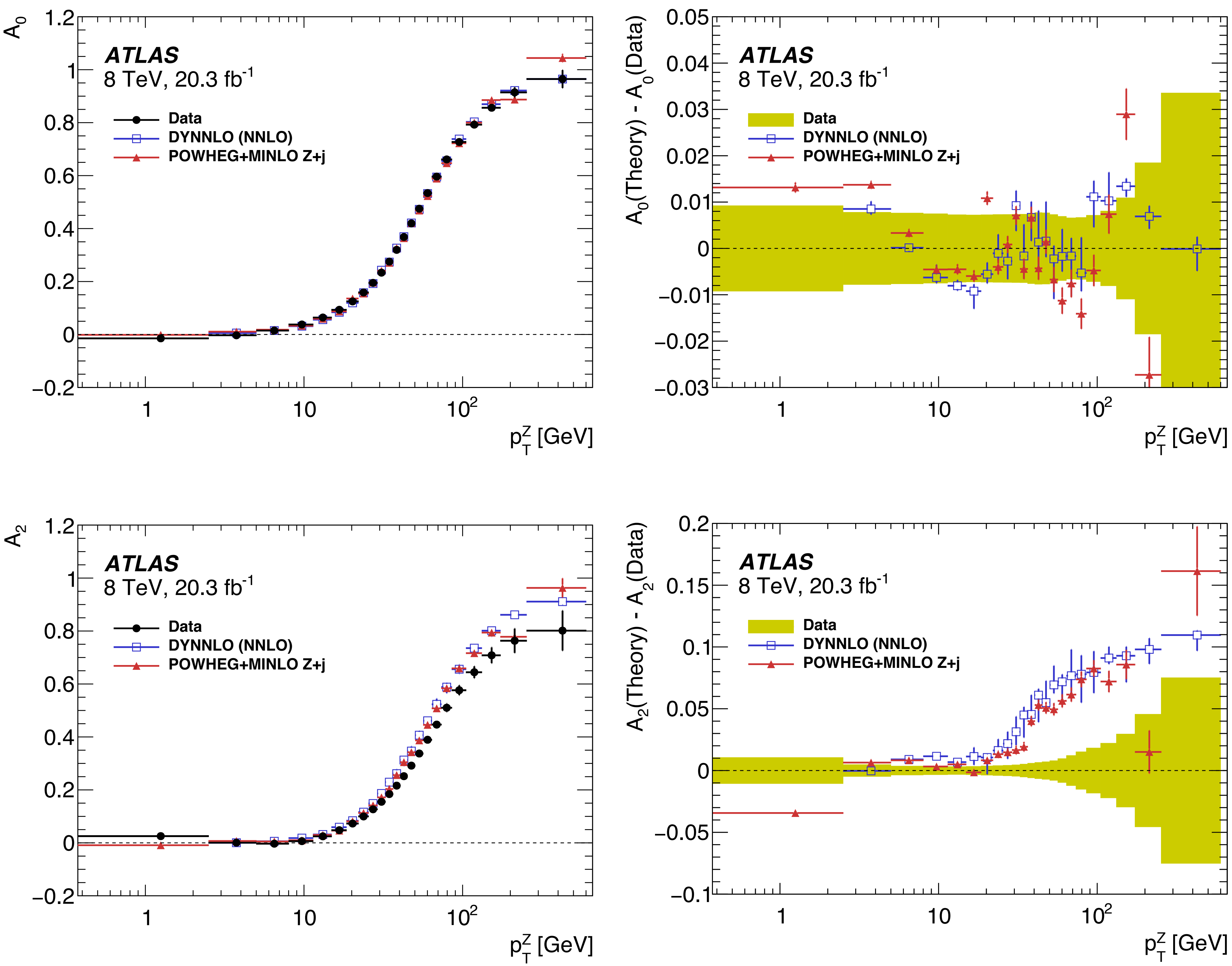
- Electron and Muon channels give consistent results
    - Similar for all A_i
- Regularization:
    - Smooth fluctuations in results & uncertainties
    - Increase correlation between bins







Measurement Results

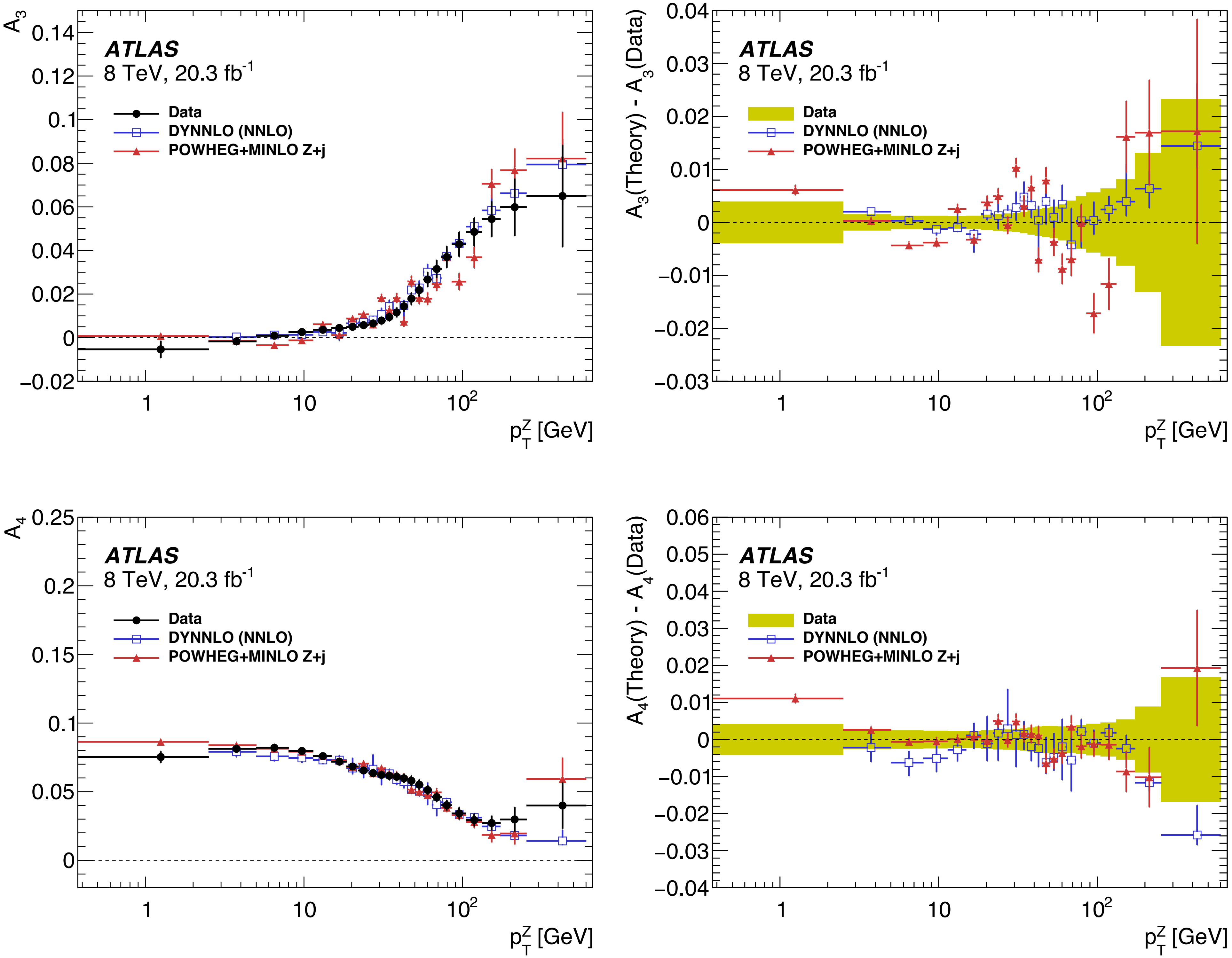


- A_0 well described by fixed order calculations
- A_2 predicted too high for large p^Z_T

▸ A_0 - A_2 predictions also off w.r.t. measurement

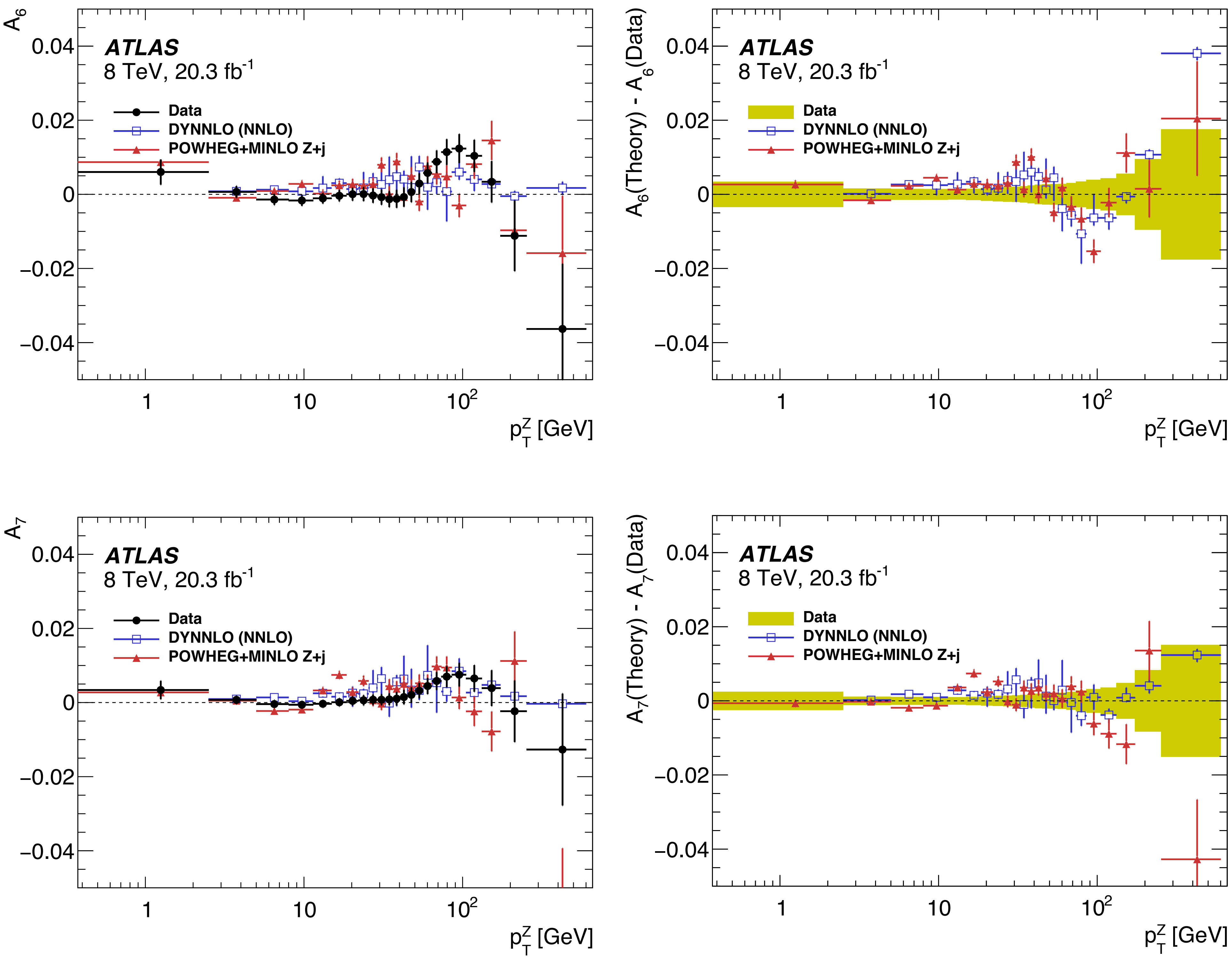
▸ Impact of higher order effects not covered in simulation

Measurement Results



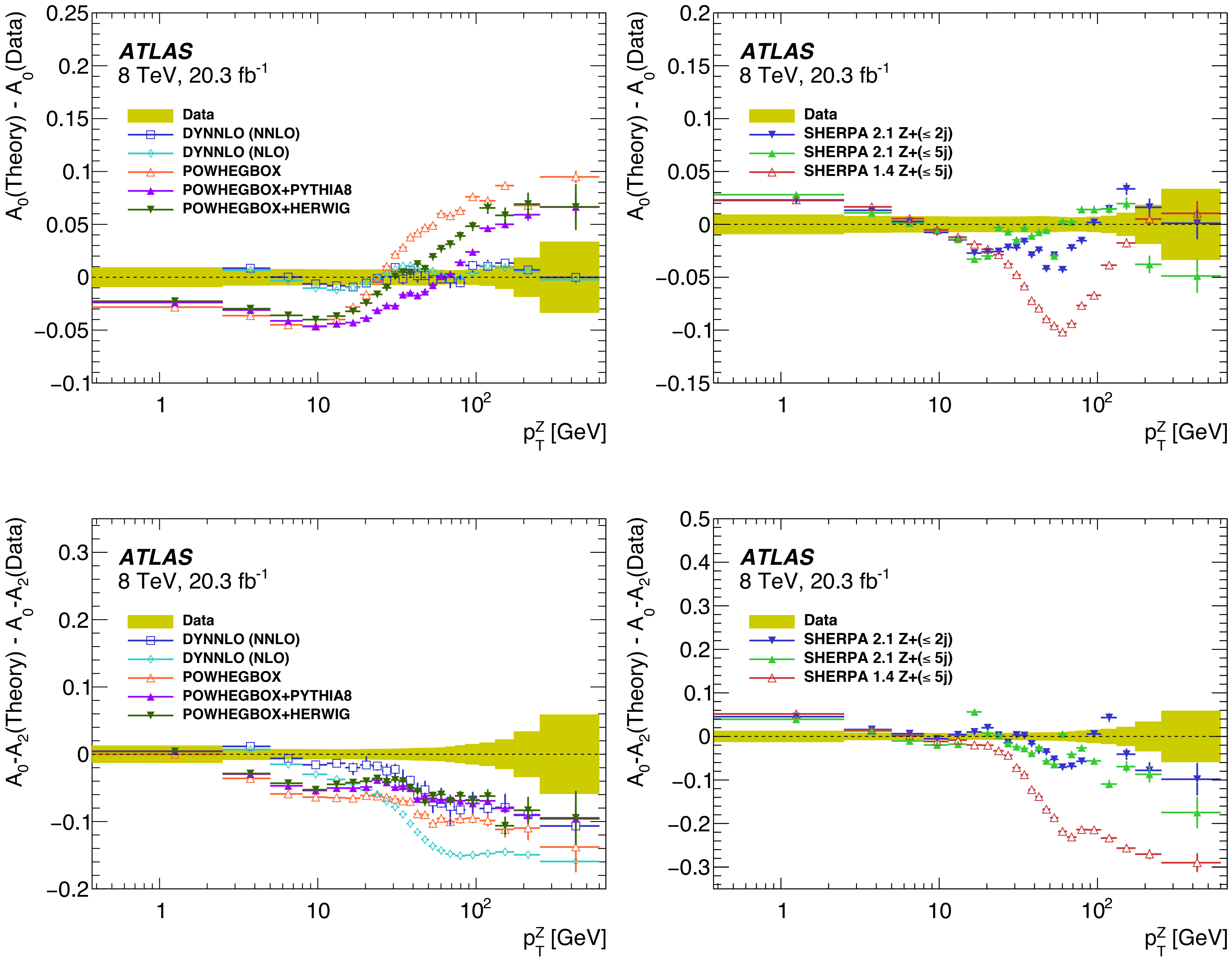
- $A_{3,4}$ well described by fixed order simulations
- Those are sensitive to the Weinberg angle

Measurement Results



- Equal to 0 @ NLO
- Higher order effects become visible
- Small discrepancy between measurement and simulation:
  - Limitations of current simulations

Comparison of various Generators



- Sherpa & PowHegBox show statistical unc. only!
- Significant differences between simulations
- DYNNLO gives best description of measured A_0
- No generator describes A0-A2
  - (Best: Sherpa 2.1)
- Improvement from Sherpa 1.4 to 2.1

Conclusions & Outlook

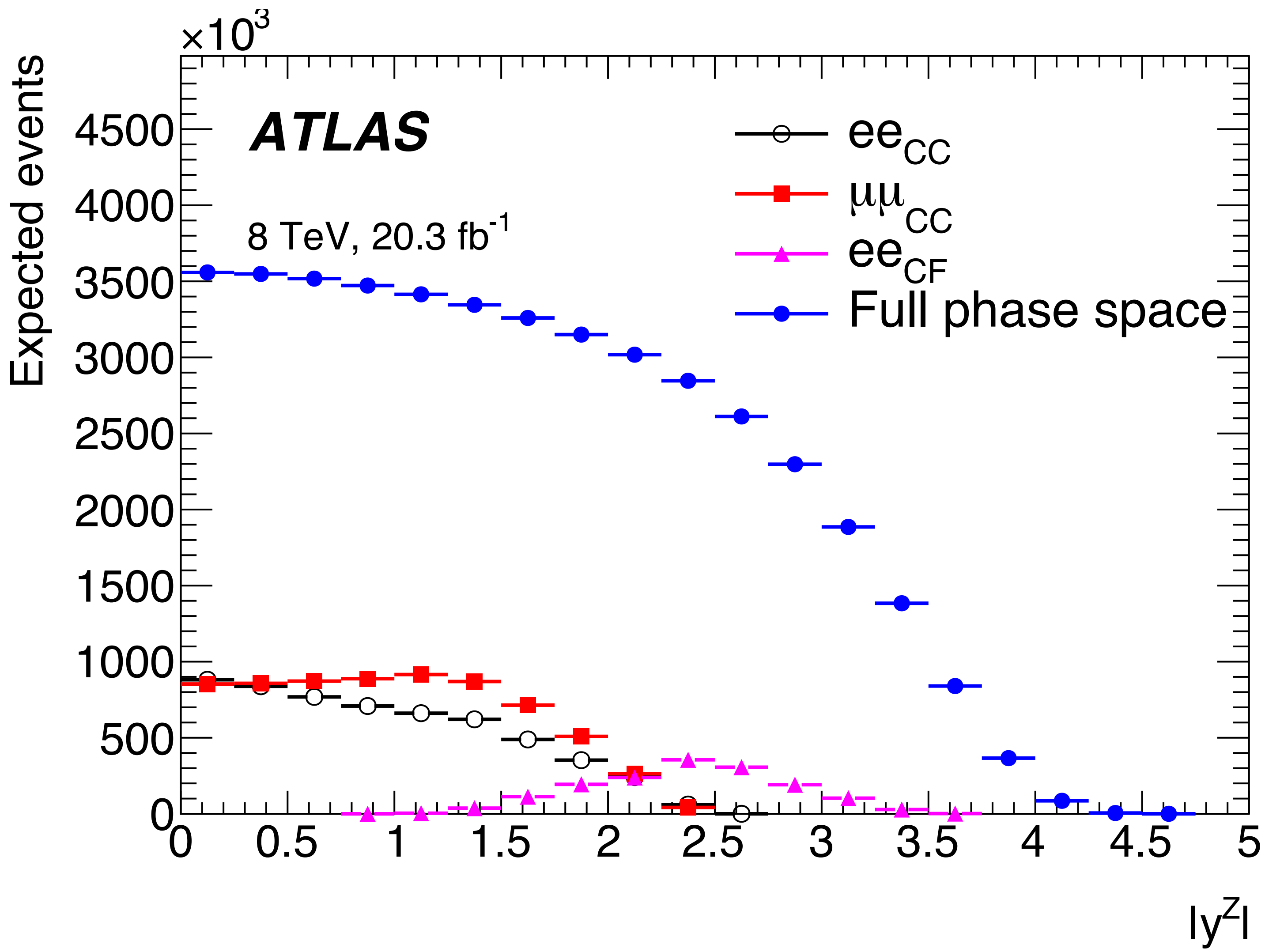
Conclusions & Outlook

- Measurement of p^{ll}_T & ϕ^*:
  - ResBos models low ϕ^* region well
  - ~10% discrepancy between simulation and measurement at Z-peak region
  - Higher order EW correction are sub-leading effects at current precision
- Measurement of the angular coefficients in Z-Boson decays:
  - Significant discrepancy between all studied simulations and the measured coefficient A_2
  - Only DYNNLO in agreement with other measured coefficients
  - A_i very sensitive probe to spin correlations in simulation process
  - Measurement could be used to extract SM parameters, e.g. the Weinberg angle

BACKUP

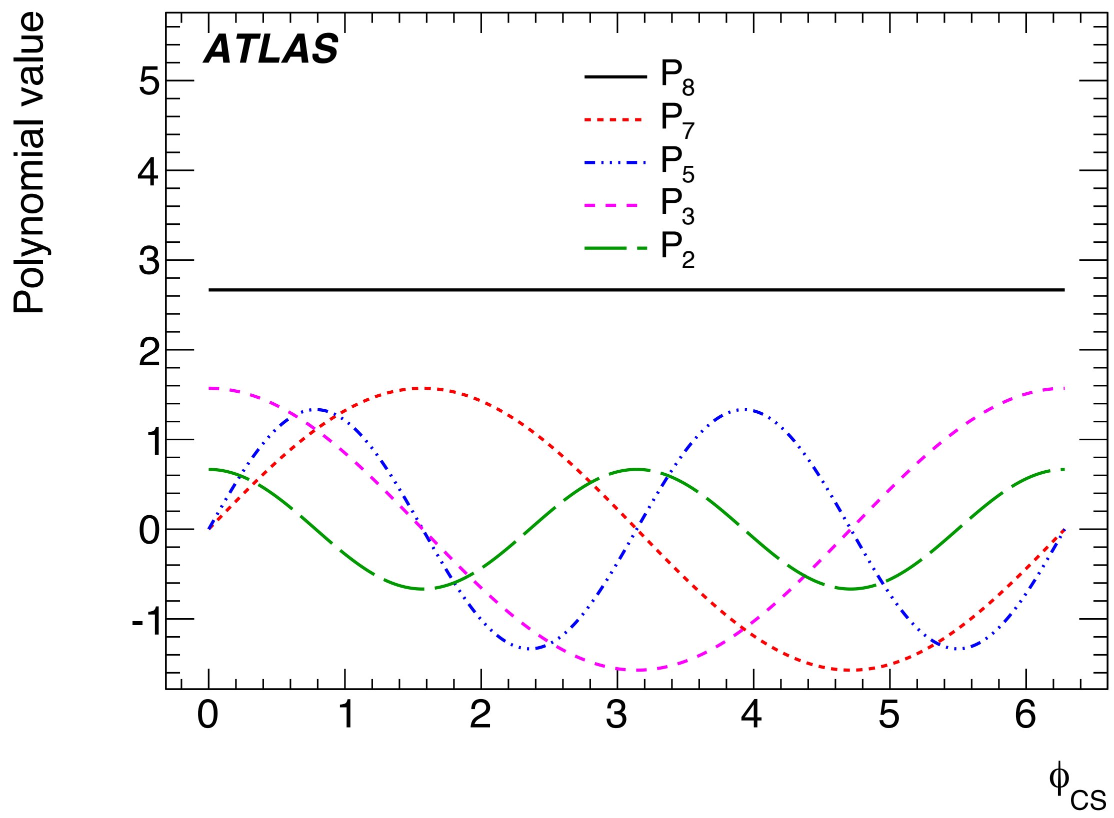
Backup slides

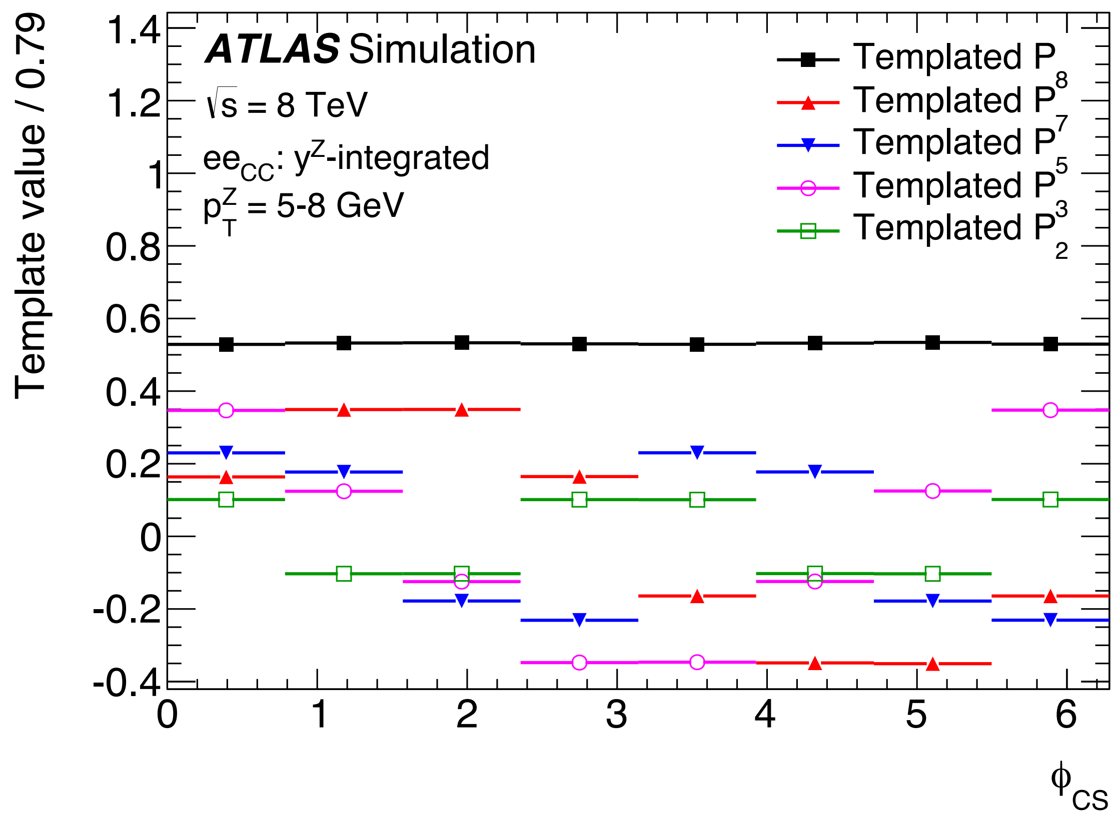
Analysis Acceptance * Efficiency for 3 considered channels



Backup slides

- Folding of phi projected polynomials





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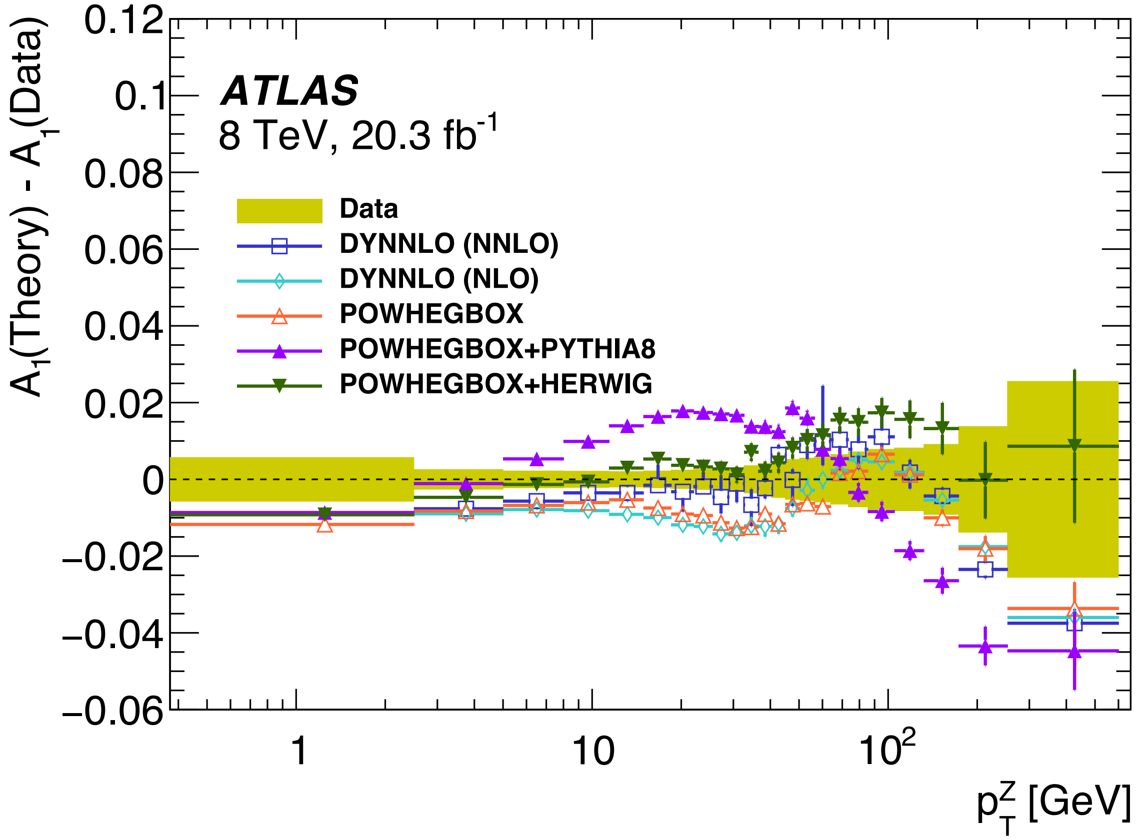

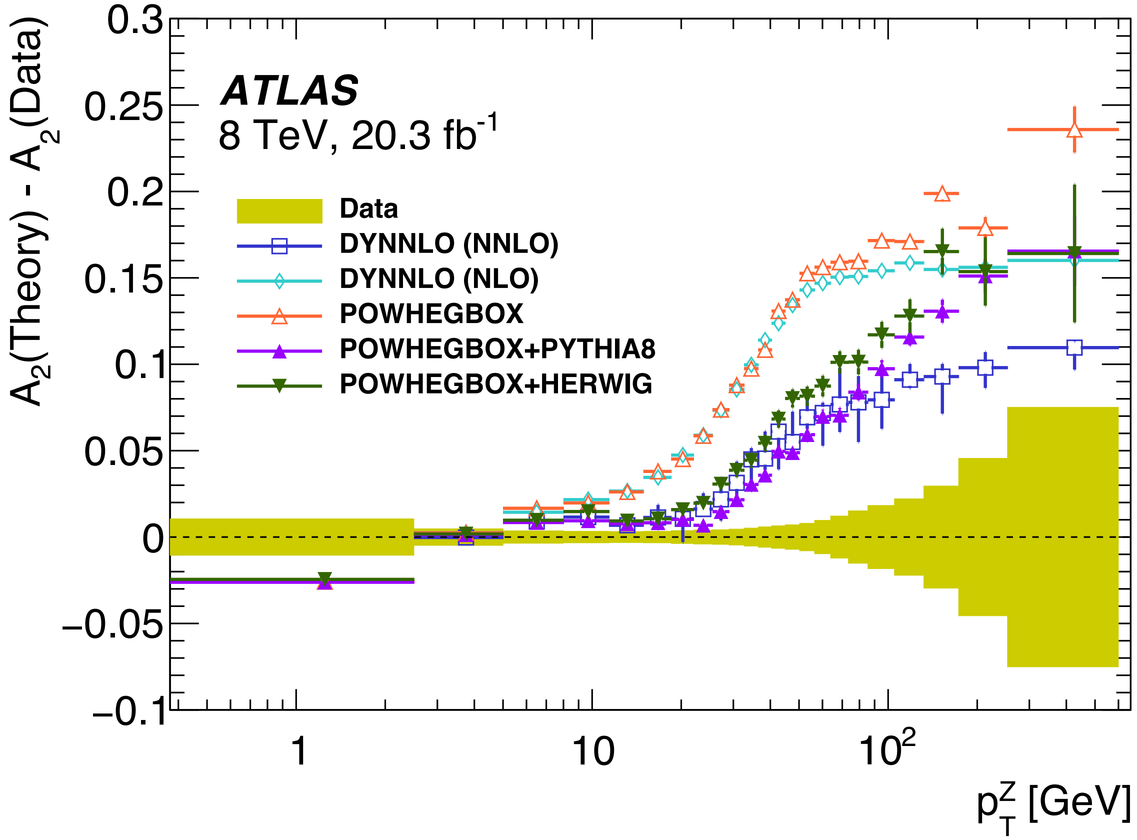

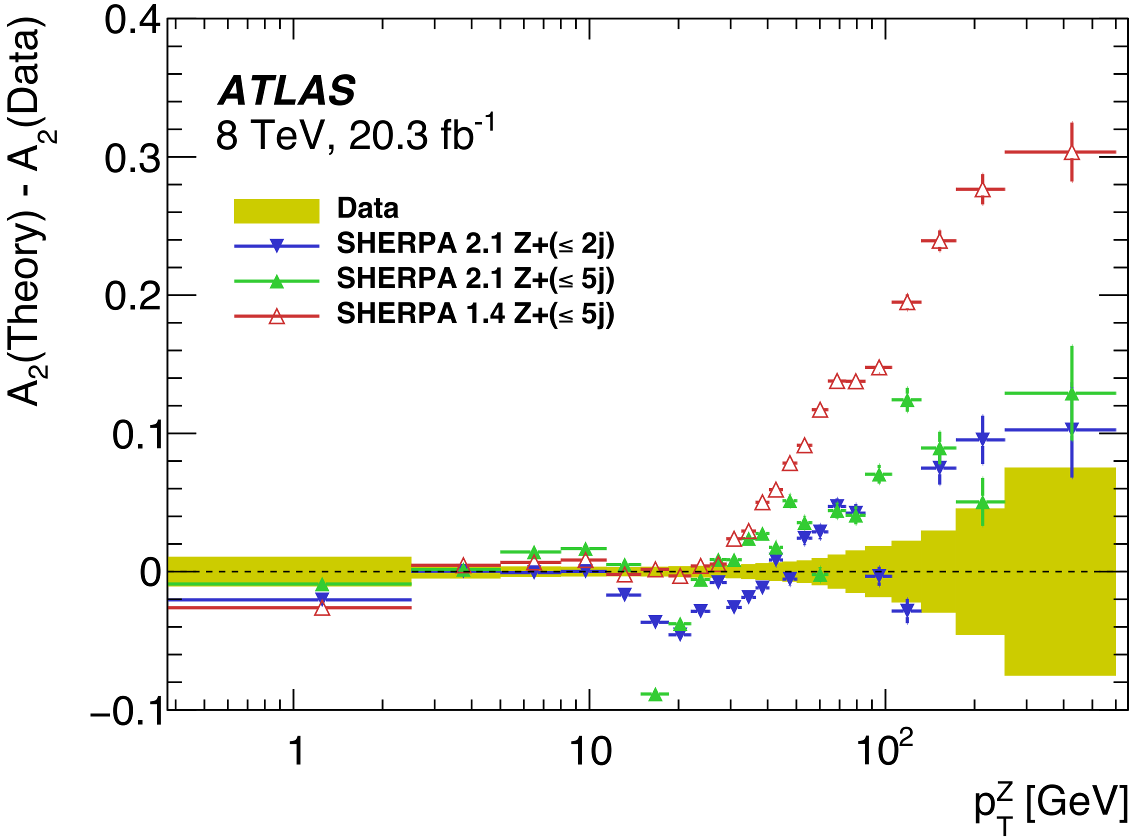

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